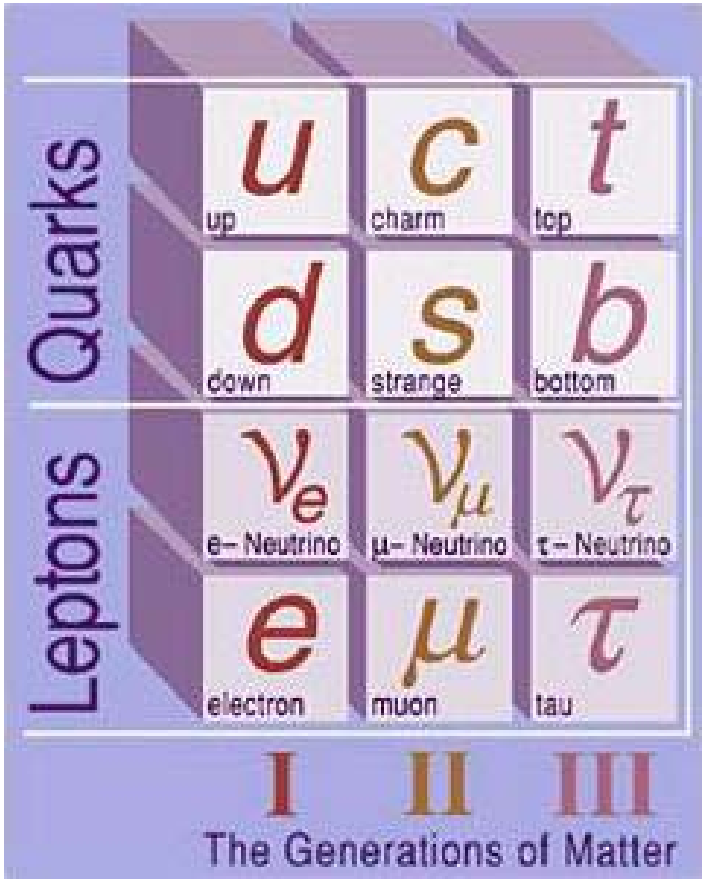
Dustmaids Down a Drafty Hall: Neutrinos at the Sudbury Neutrino Observatory

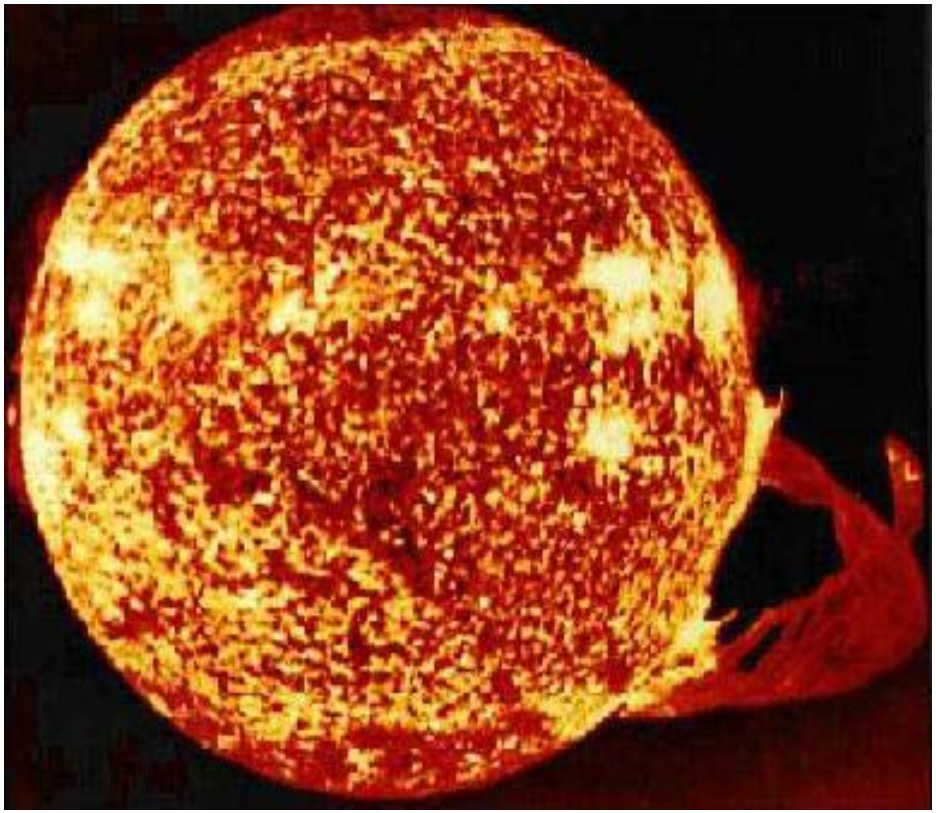
Joshua R. Klein
The University of Texas at Austin

Sambamurti Lecture,
Brookhaven National Laboratory

- **Neutrinos**
- **The Sun**
- **Solar Neutrino Problem**
- **Sudbury Neutrino Observatory**
- **Results and the Future**

Two Stories

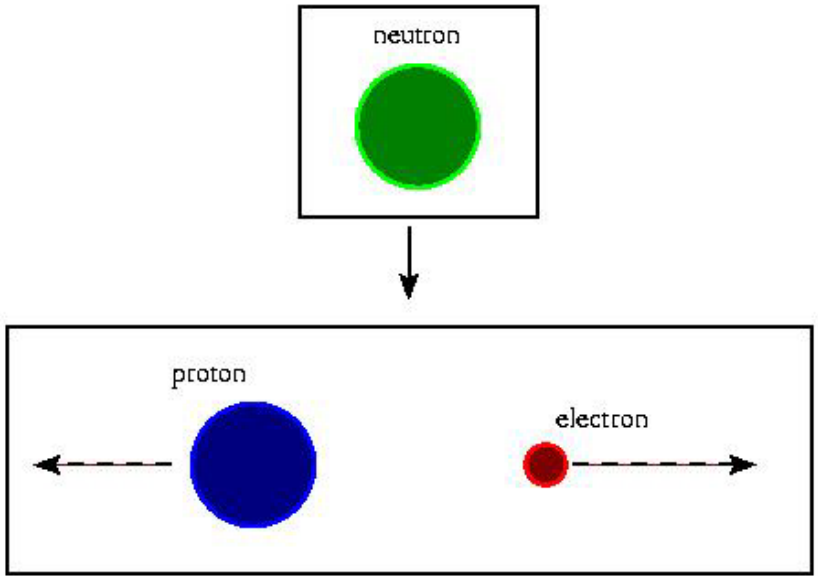

Quarks
Leptons
u
up
c
charm
t
top
d
down
s
strange
b
bottom
ν_e
e– Neutrino
ν_μ
μ– Neutrino
ν_τ
τ – Neutrino
e
electron
μ
muon
τ
tau
I
II
III
The Generations of Matter



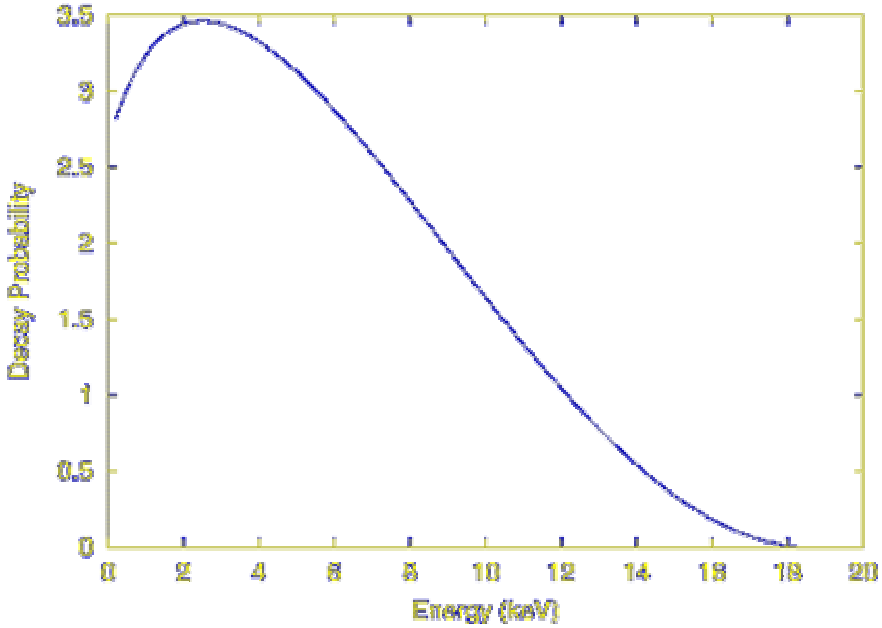
Invention of the Neutrino

Beta decay mystery:

2-body decay should give mono-energetic electron



But observed spectrum is continuous



Invention of the Neutrino

Wolfgang Pauli suggests a third particle (1930)

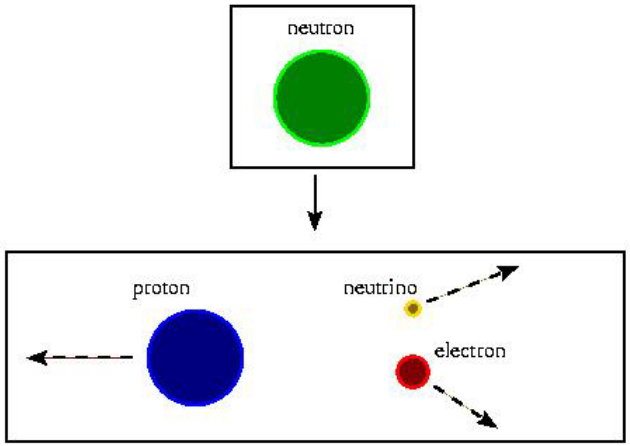



Photo: AIP, Emilio Segrè Visual Archives

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Designed to be impossible to detect…almost.

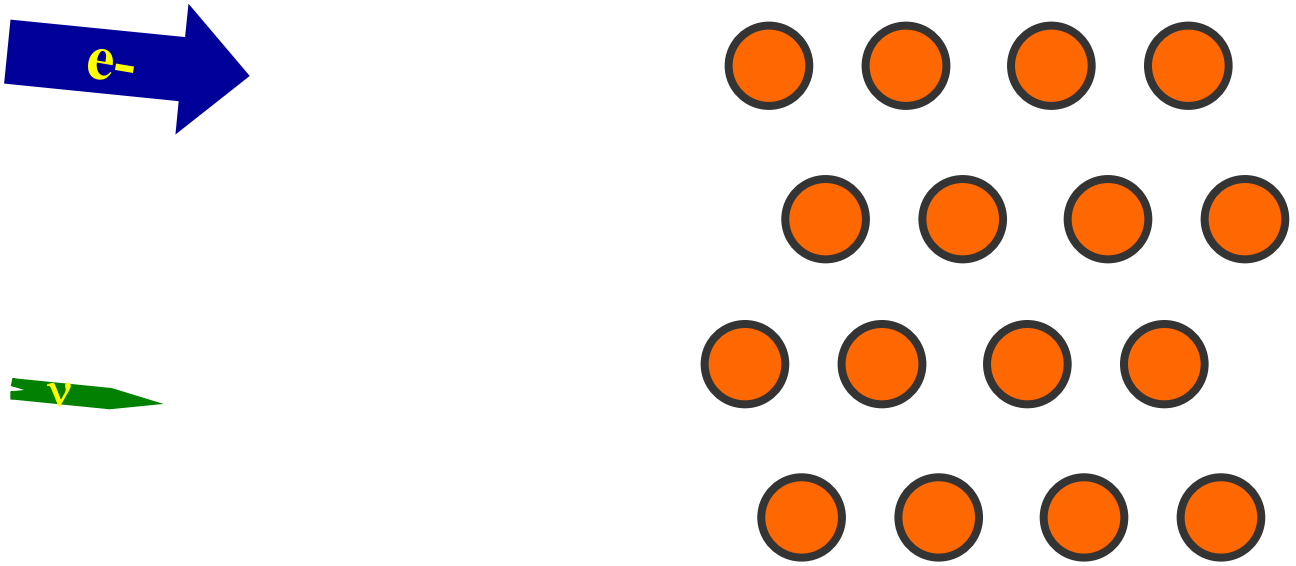
Neutrino Poetry

"Cosmic Gall", by John Updike In *Telephone Poles And Other Poems (1960)*

NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

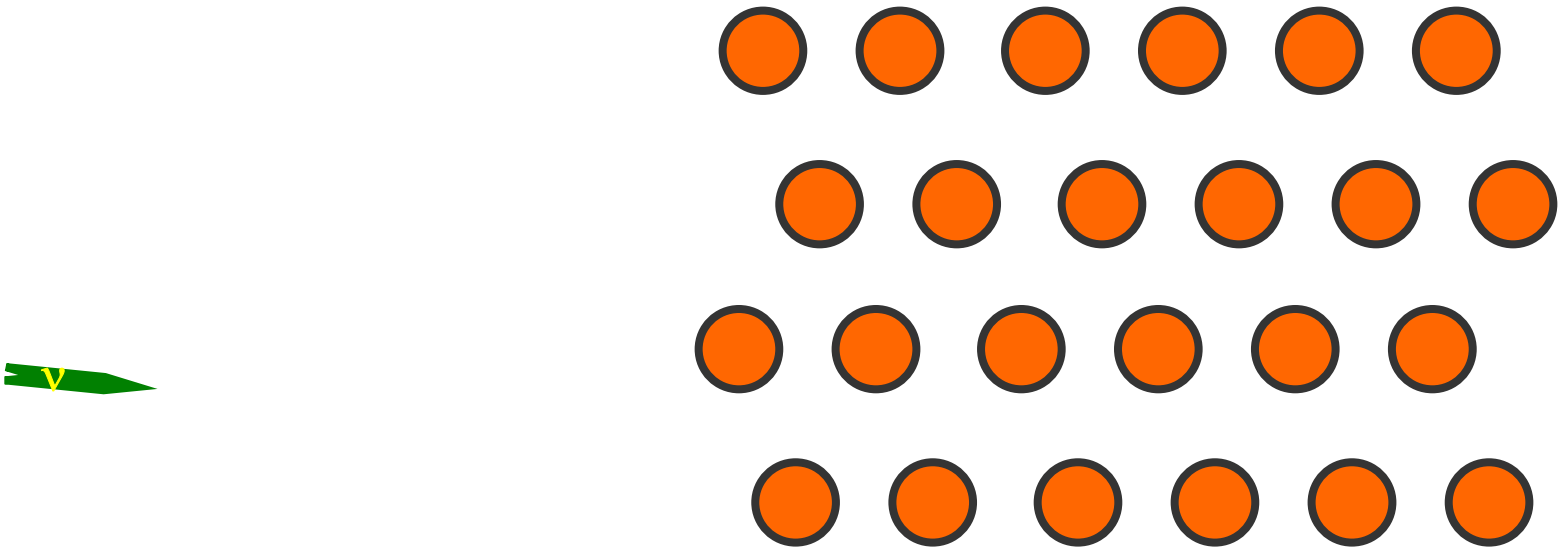
Detecting Neutrinos

- Weakly Interacting Signal



Detecting Neutrinos

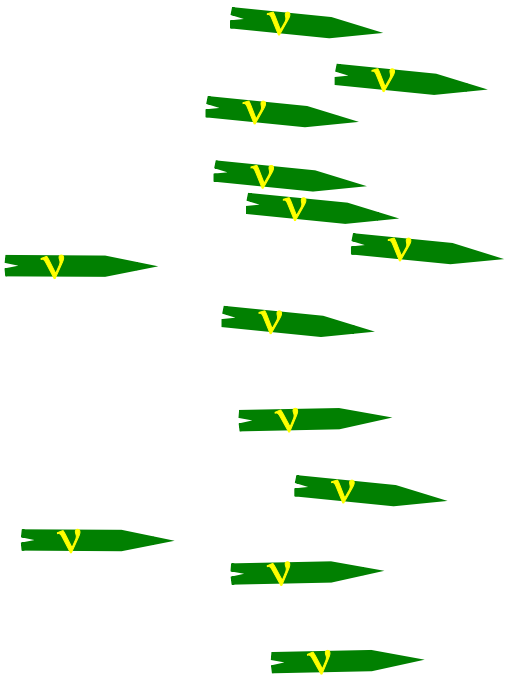
- Weakly Interacting Signal

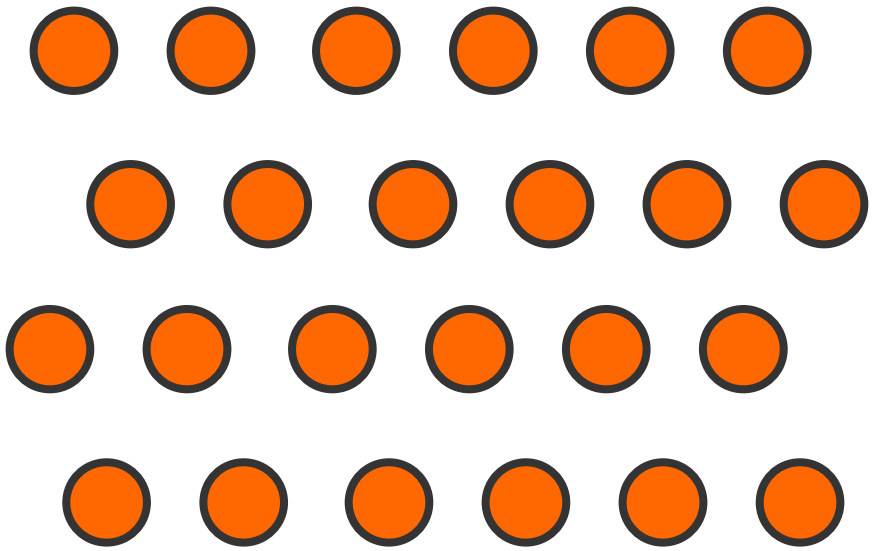


Add more matter…

Detecting Neutrinos

➢Weakly Interacting Signal





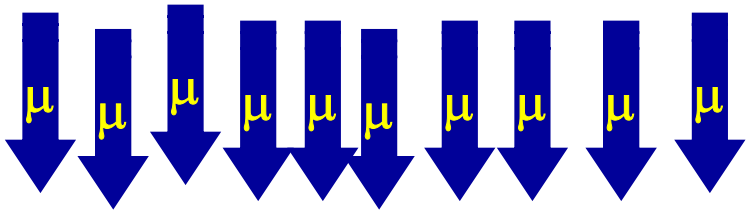
Or use more neutrinos…

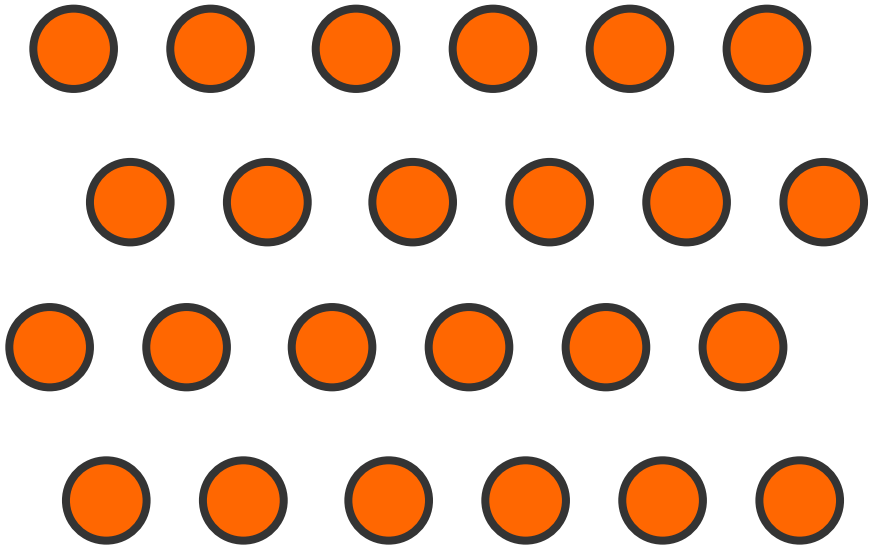
CNB *Radioactive nuclei* *Reactors* *Supernovae* *Accelerators*

The Sun *Atmospherics* *Cosmic sources*

Detecting Neutrinos

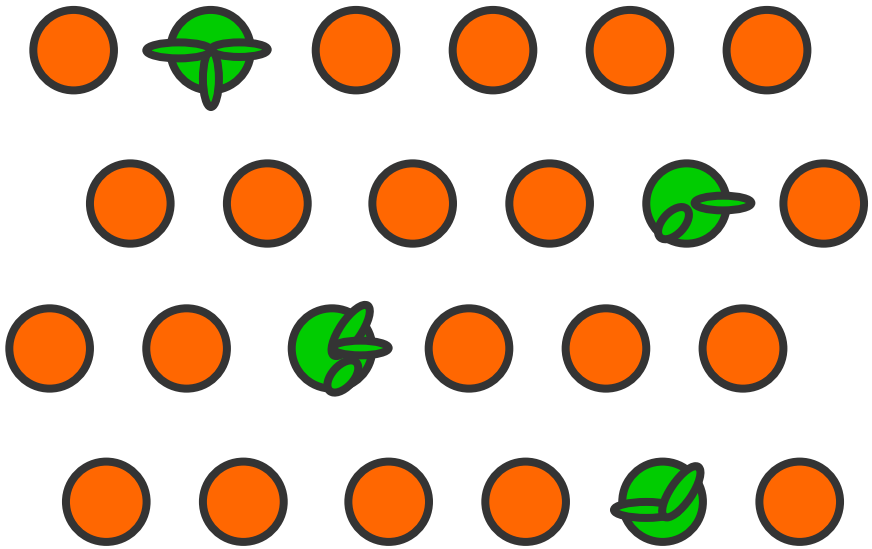
- Backgrounds: Muons from Space



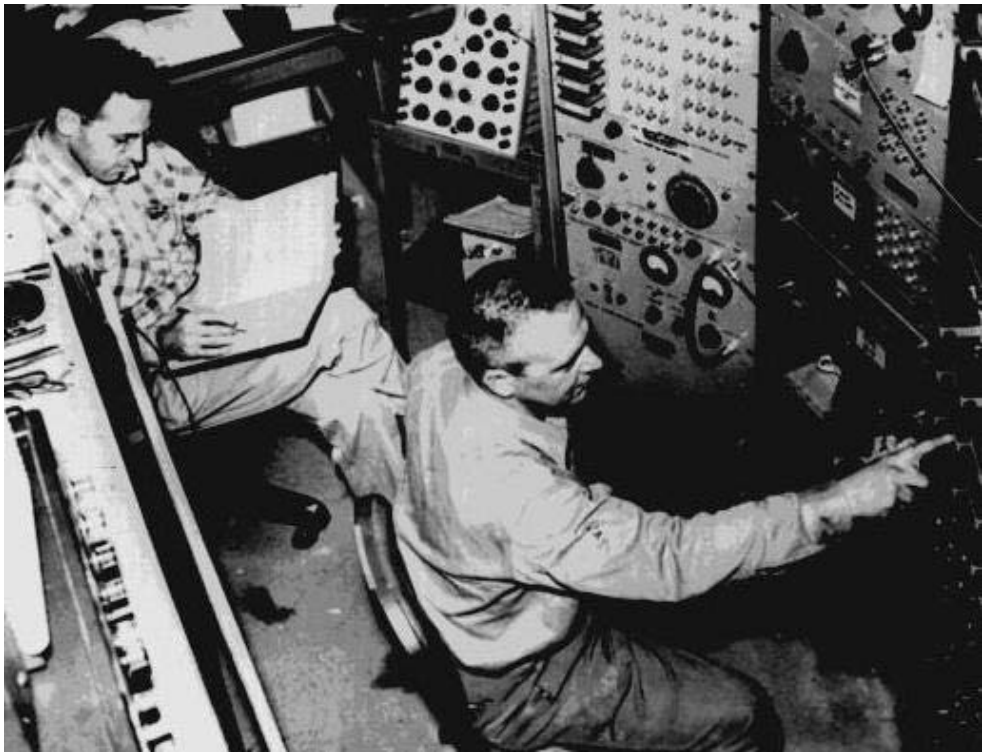


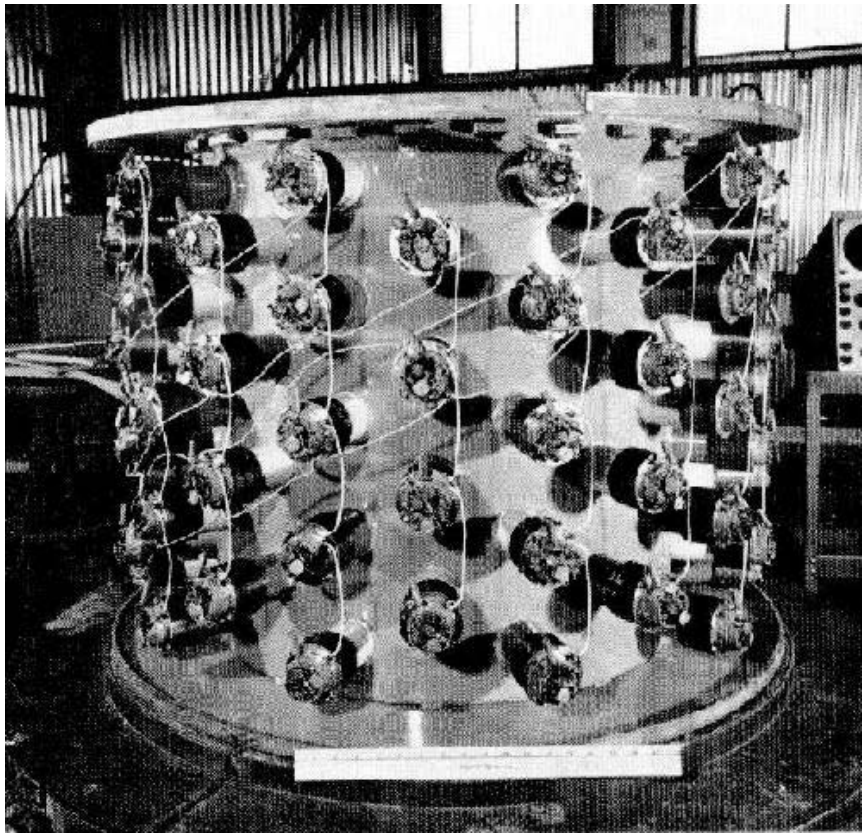
Detecting Neutrinos

- **Backgrounds: Natural Radioactivity**



Discovery of the Neutrino

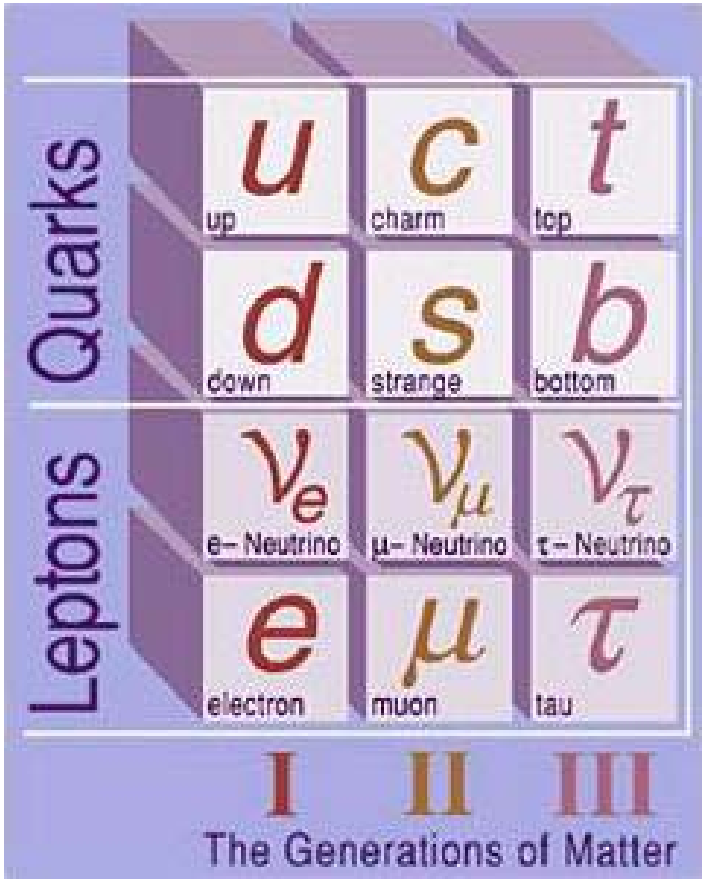




→ **Reines and Cowan see convincing signal in 1956**

`Standard Model' Neutrinos

Our best theory of the microscopic Universe…



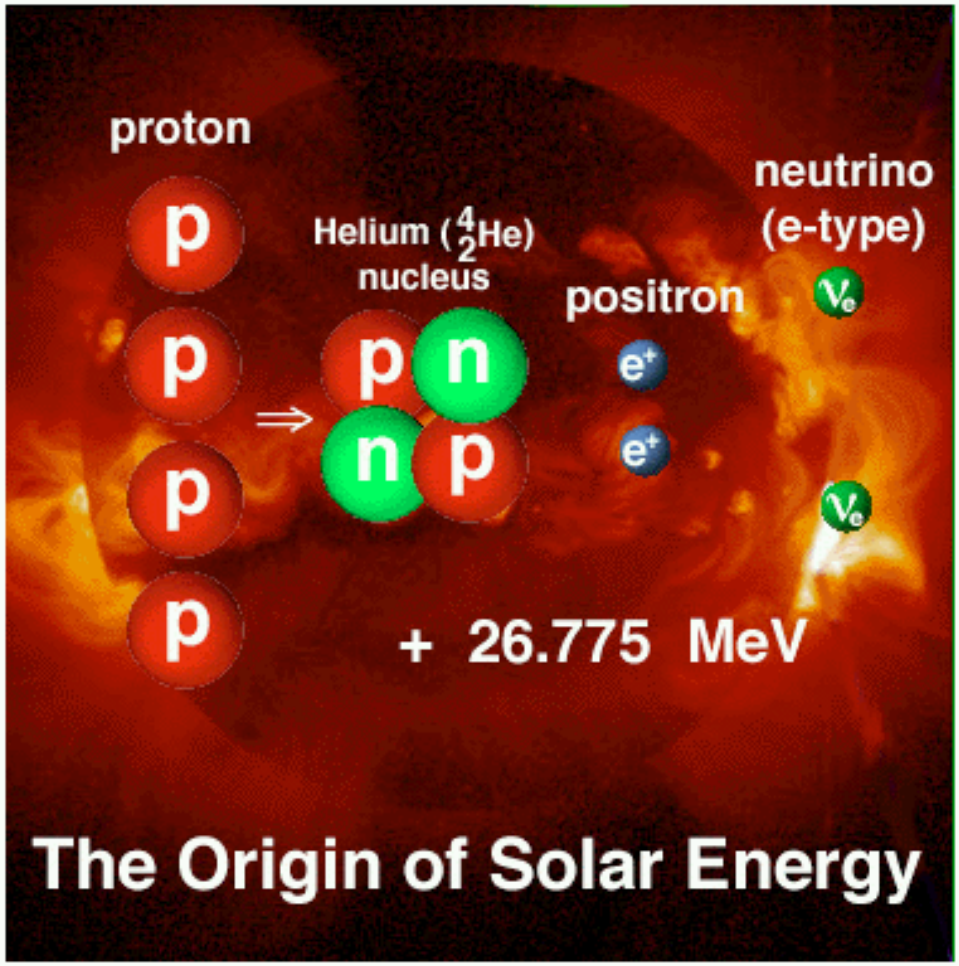
Neutrinos:

- **Come in three `flavors' (ν_e, ν_μ, ν_τ)**
- **Are massless**
- **Interact *weakly***
- **Cannot change flavor**

OVER TWENTY YEARS OF TESTS CONFIRMED EVEN THE MOST SUBTLE PREDICTIONS.

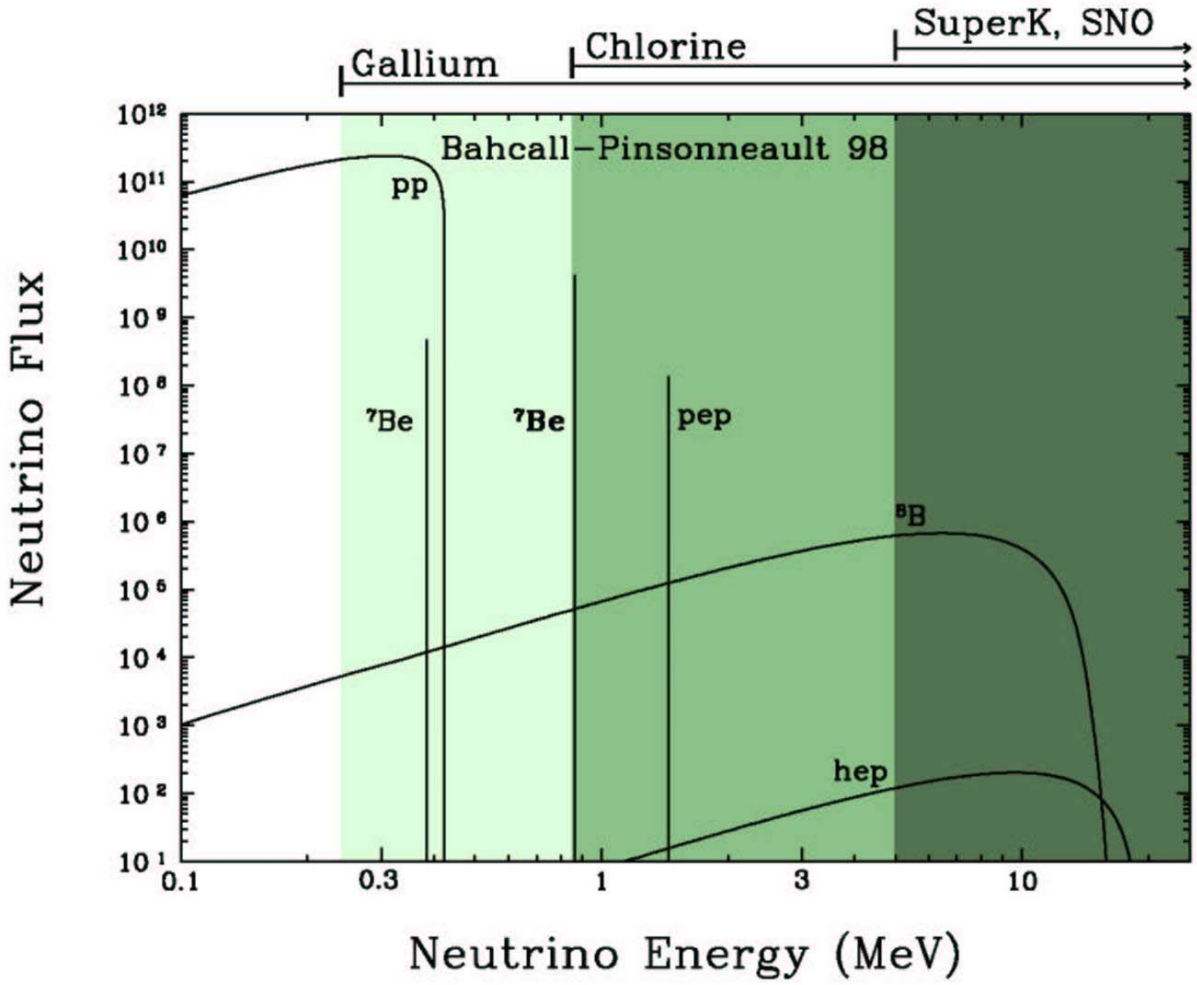
Solar Fusion

➢ On the Other Hand…



Solar Neutrino Spectra

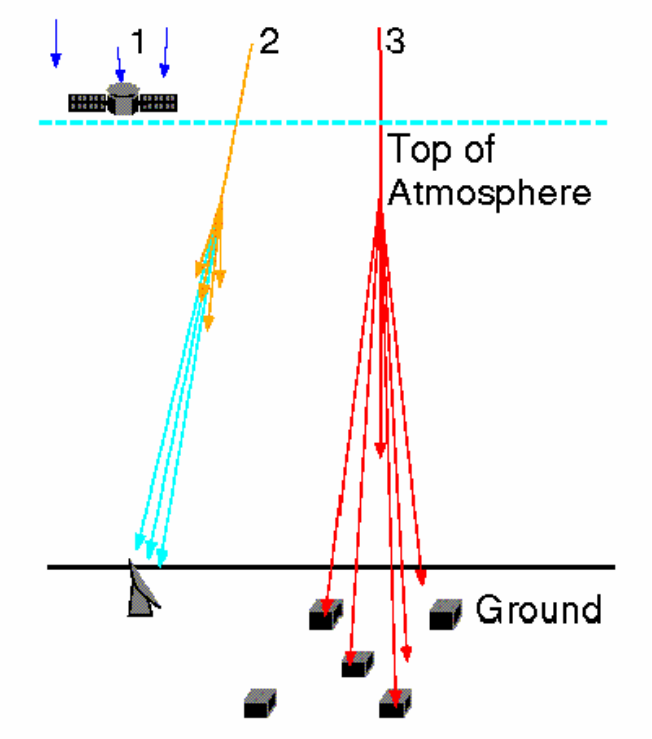
…within the `Standard Solar Model'



Solar Neutrino Experiments

Experiments need to be:

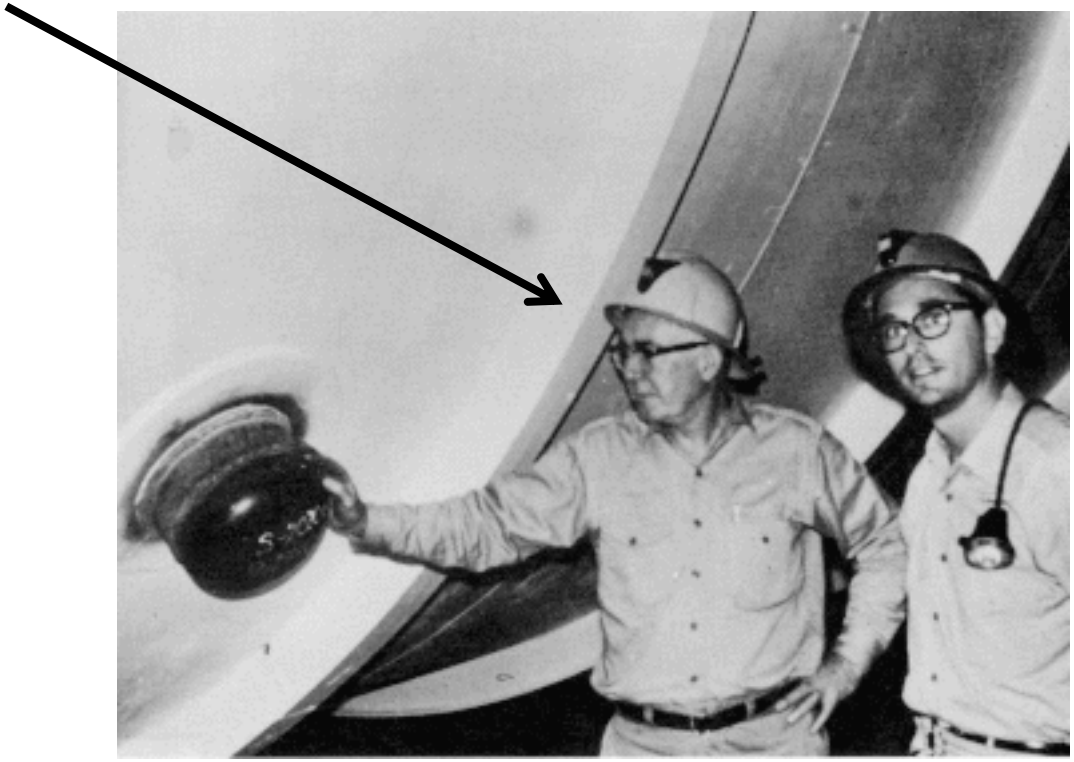
- Big ⟶ to detect weakly interacting ν's
- Deep ⟶ to get away from cosmic rays



- Clean ⟶ to reduce radioactivitiy

Solar Neutrino Experiments

Won Nobel Prize this year!



First experiment by Davis *et al* in 1960's

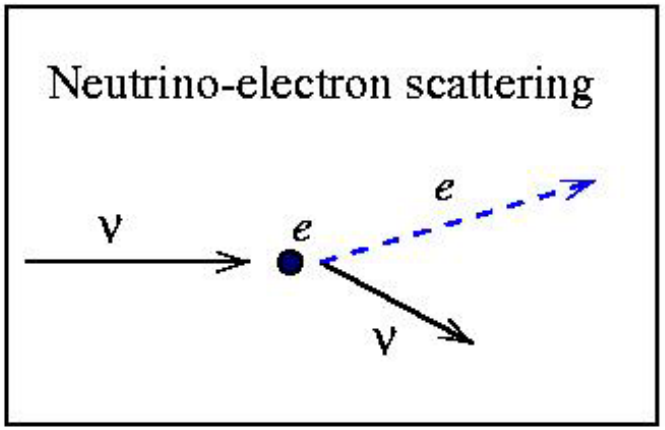
Radiochemical Method (Chlorine):

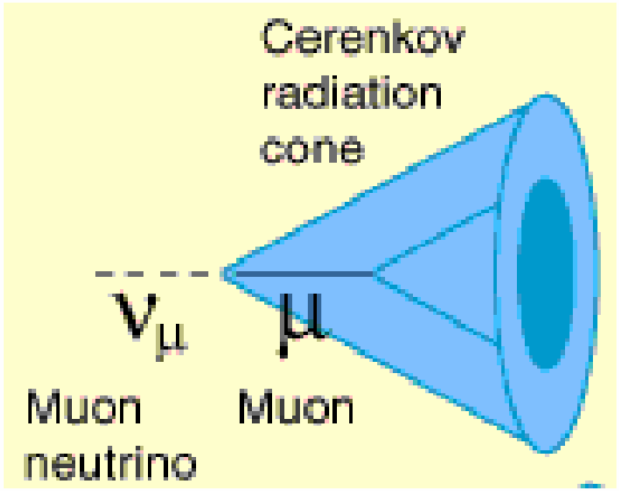
⟶ Found ~ 1/3 of expected rate!

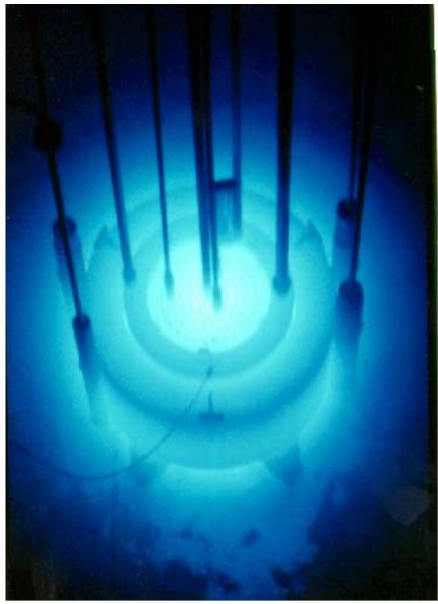
Solar Neutrino Experiments

Water Cerenkov method:

$\nu_x + e^- \longrightarrow \nu_x + e^-$







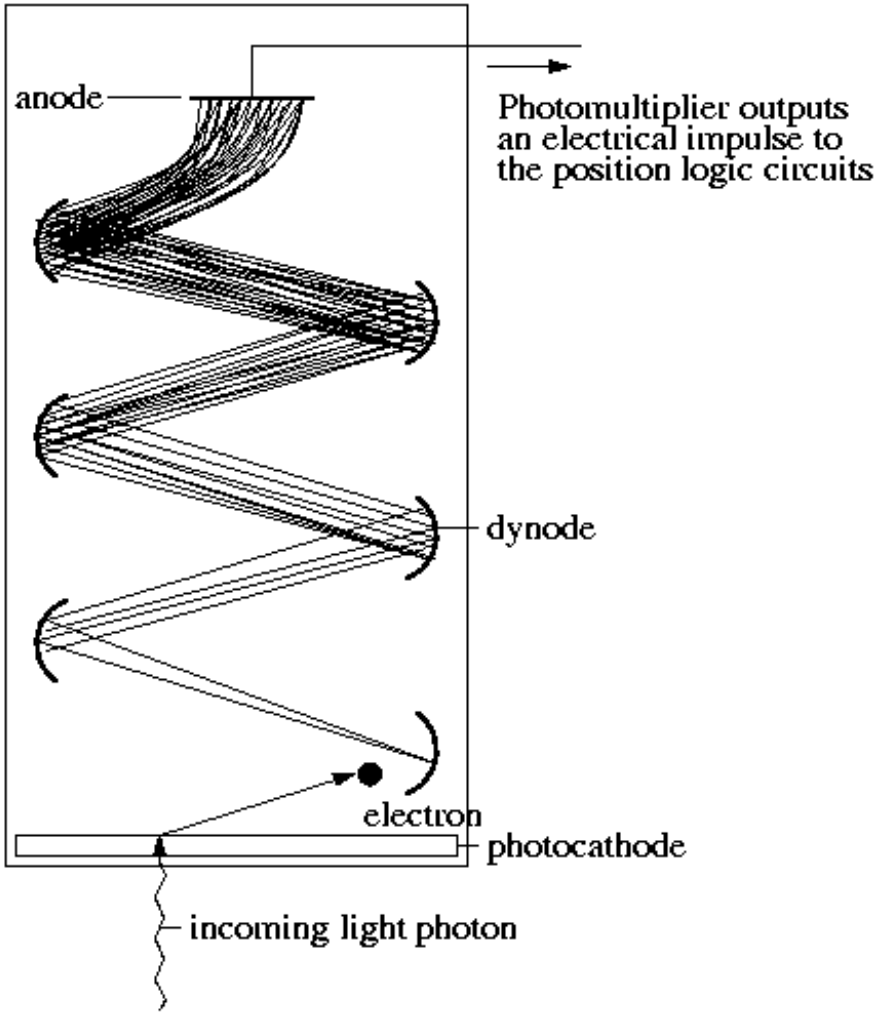
Solar Neutrino Experiments

Water Cerenkov method:

$\nu_x + e^- \longrightarrow \nu_x + e^-$

Only 50 detectable photons for each ν interaction…

…but photomultiplier tubes (PMTs) can see even 1 photon.



A Photomultiplier Tube

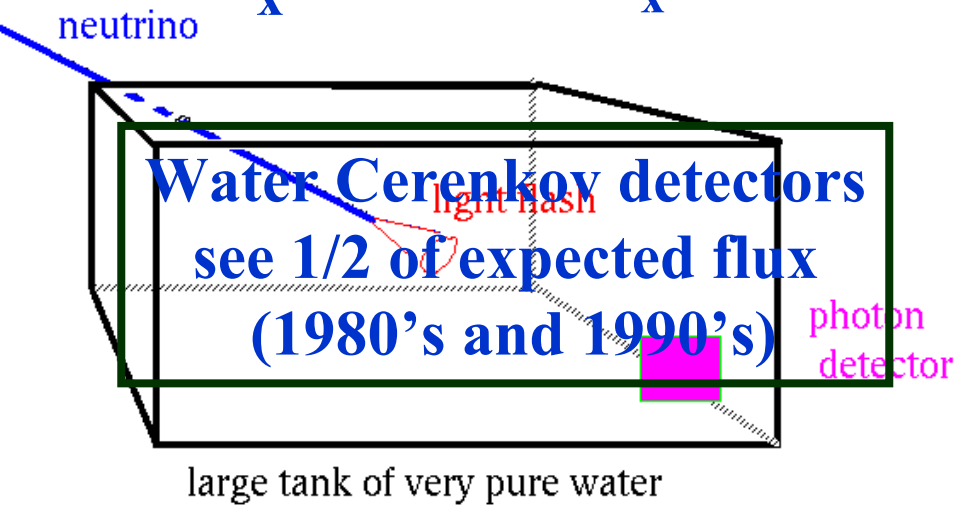
Experimentalists design

- **Detection electronics**
- **Readout electronics and software**
- **Analysis software…**

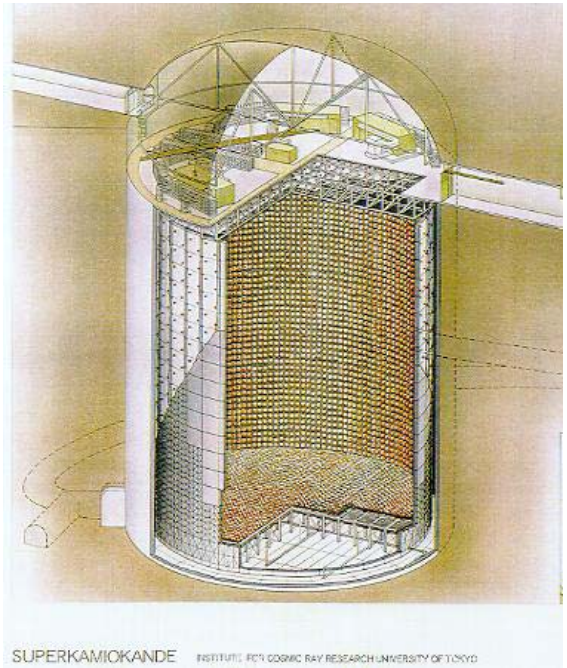
Solar Neutrino Experiments

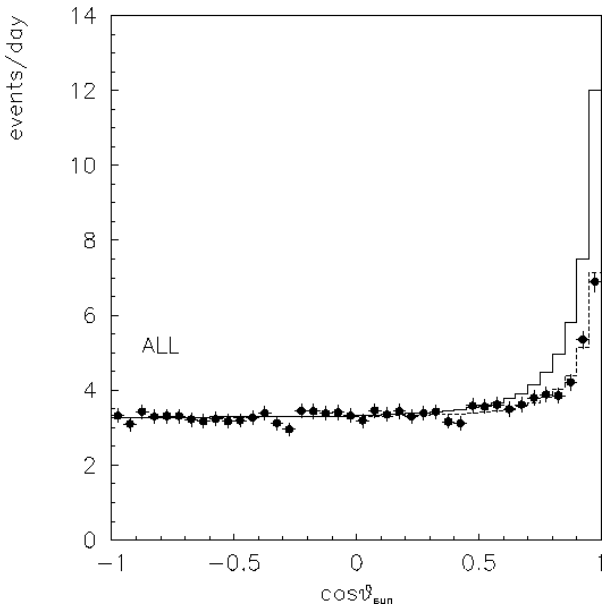
Water Cerenkov method:

$$\nu_x + e^- \longrightarrow \nu_x + e^-$$



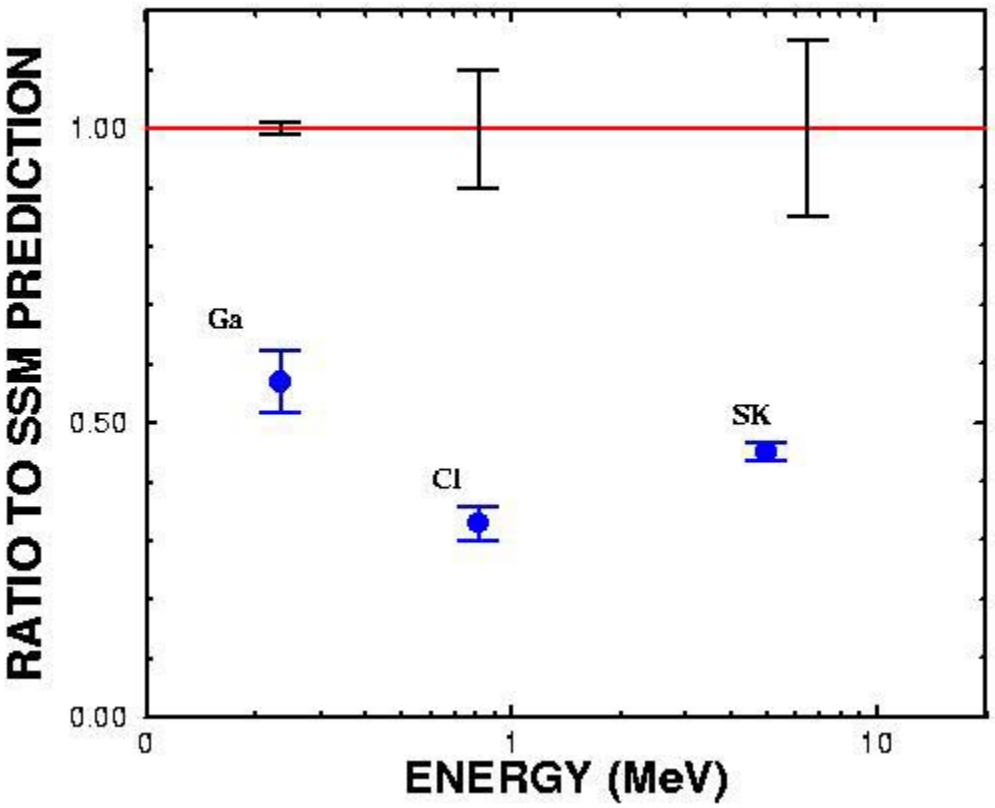
Water Cerenkov detectors see 1/2 of expected flux (1980's and 1990's)





After Six Solar ν Experiments

- 3 Gallium (Radiochemical)
- 1 Chlorine (Radiochemical)
- Kamiokande + Super-Kamiokande (Water Cerenkov)



What's Going On??

- Are experiments wrong?
- Or Solar Theory?
- Or the neutrino?

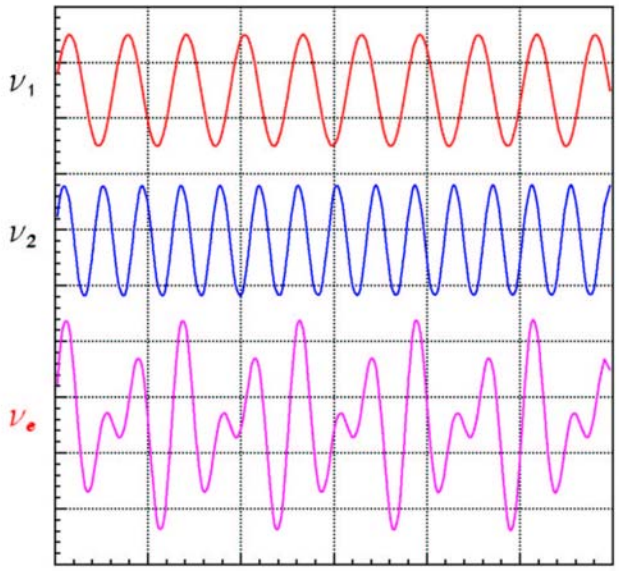
Introduction to ν Oscillations

"Most natural explanation for measurements"

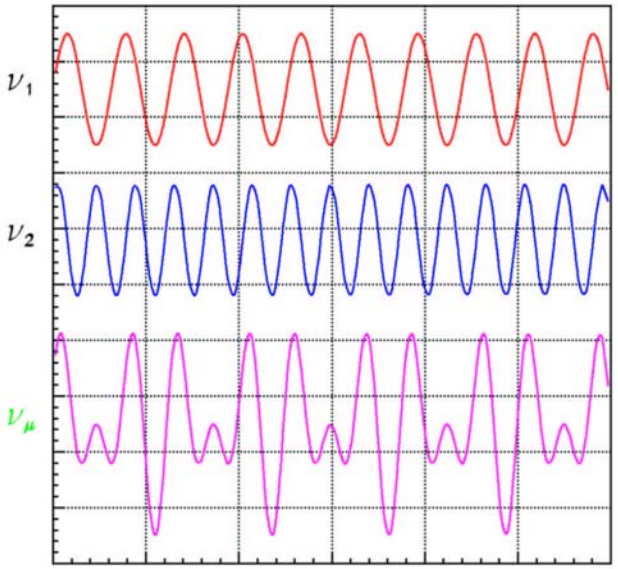
How can neutrinos change from one type to another?

Particles have wavelike properties.

If a ν_e is the sum of two waves



and a ν_μ is the sum of those two waves shifted relative to one another



then a ν_e can change into a ν_μ if Wave 1 (ν_1) travels at a different speed than Wave 2 (ν_2)

This can happen if the neutrinos have different masses.

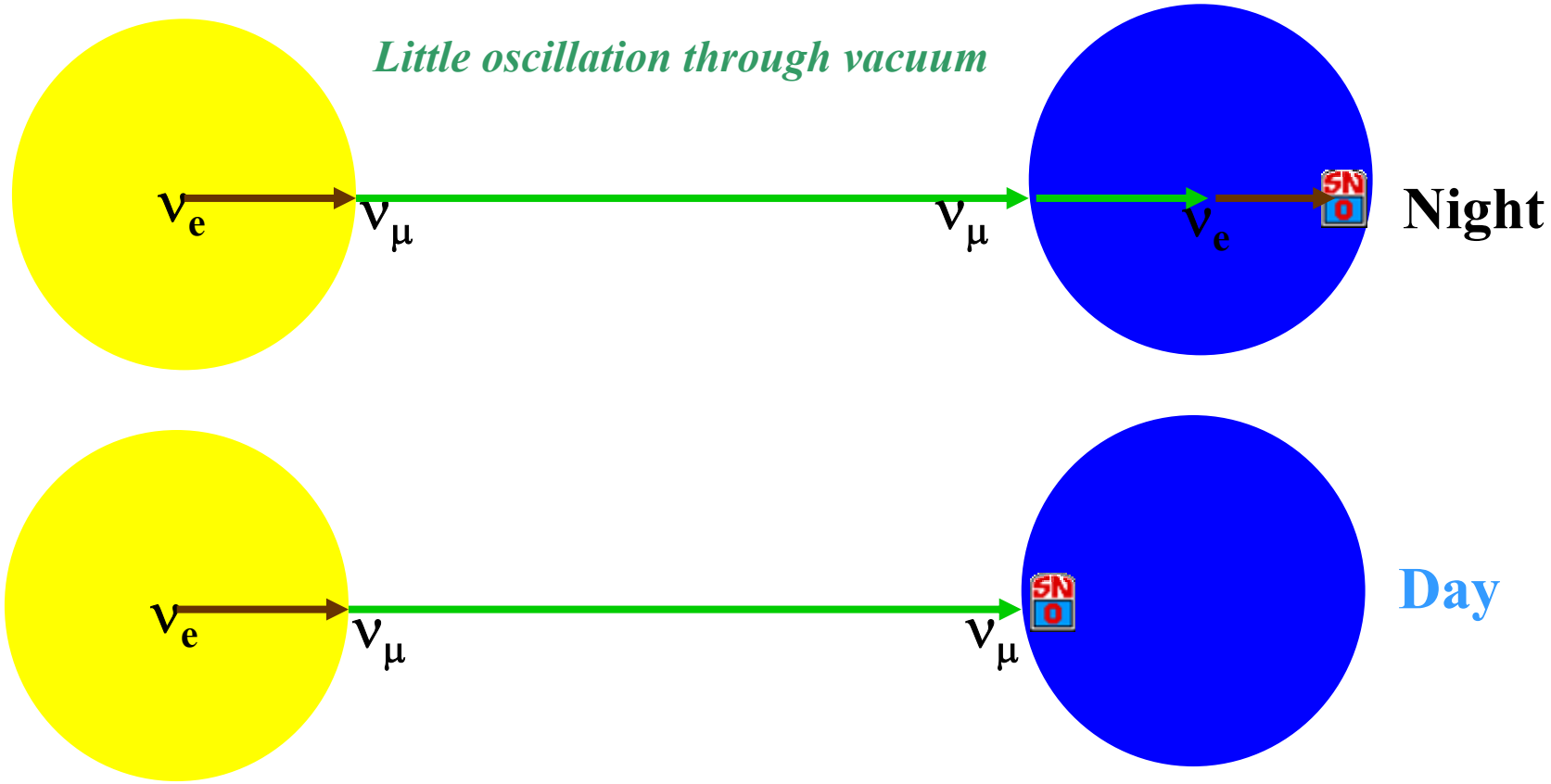
And can be enhanced if ν's travel though dense matter.

Oscillation Mechanism (Matter)

➢ Day-Night asymmetry

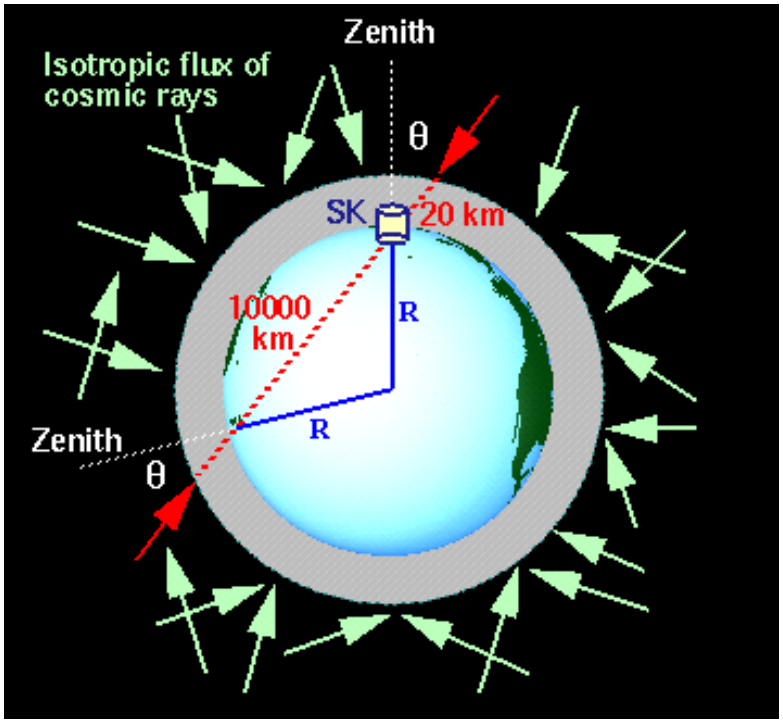
$\nu_e \rightarrow \nu_\mu$ conversion in matter

$\nu_\mu \rightarrow \nu_e$ regeneration in matter



Evidence for Neutrino Oscillations

`Atmospheric' ν's in Kamiokande II, IMB, and Super-Kamiokande:



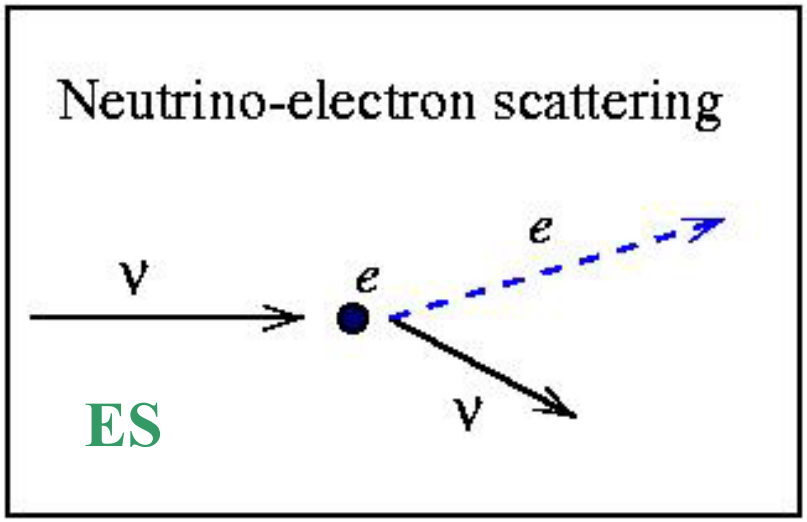
→ Only half the number of ν_μ's coming upward

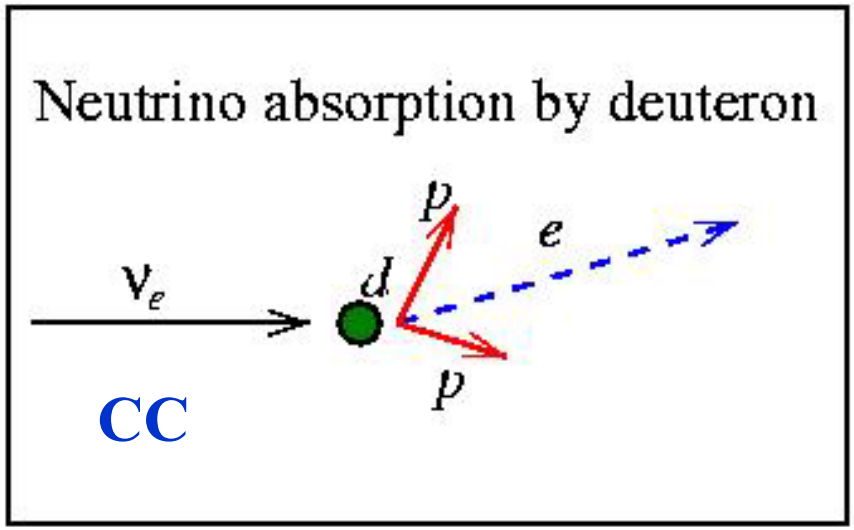
The Story So Far

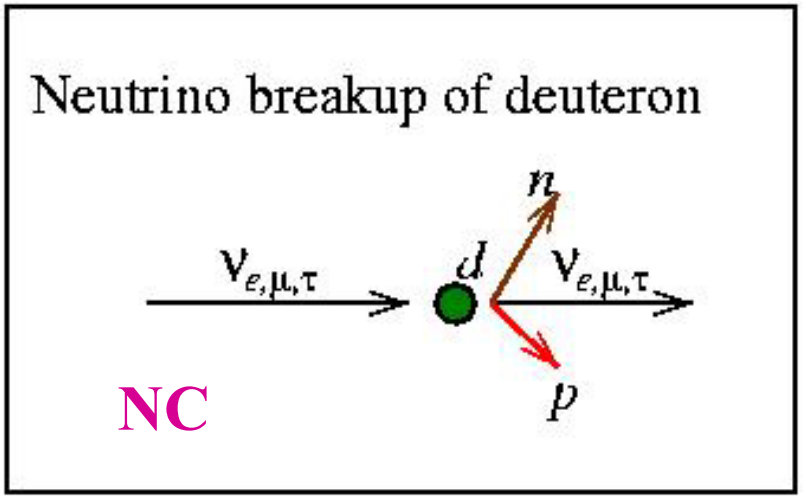
- Solar ν fluxes inconsistent with models
- Oscillations provide a nice explanation
  - ***But unproven for solar ν's***

- Solar physics with ν's still on hold…

Herb Chen's Idea (1984): Use Heavy Water







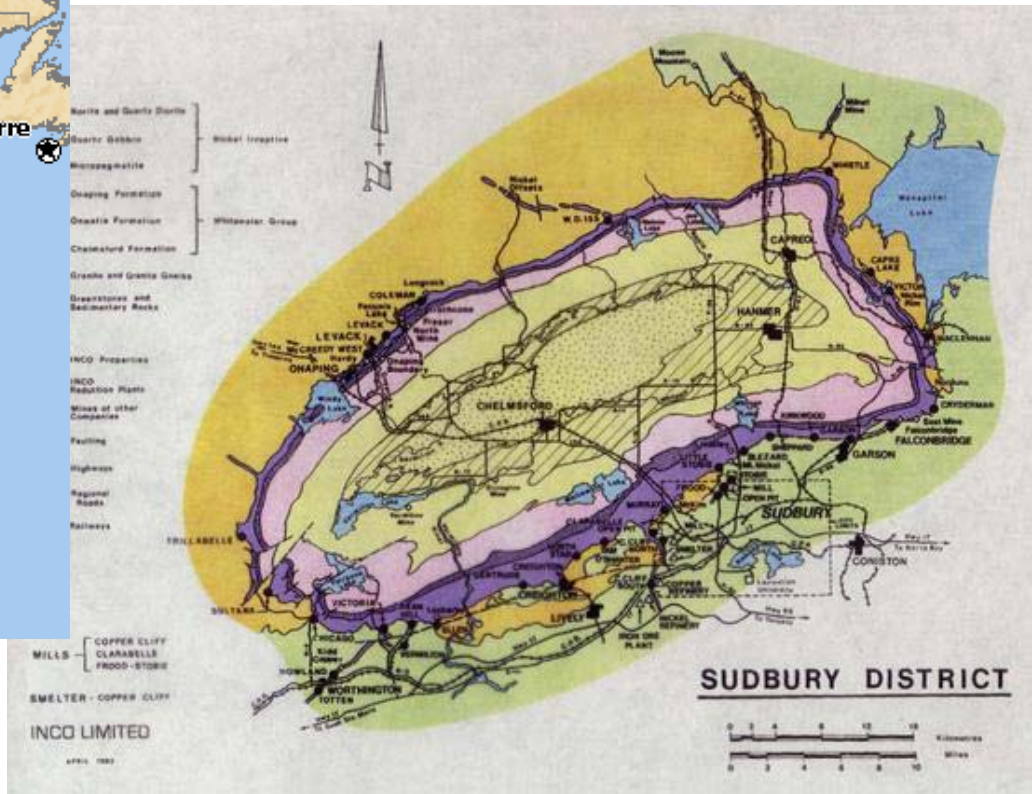
Sudbury Neutrino Observatory

Main goal:

Look directly for changed neutrinos!

Where to put it?

Sudbury, Ontario (Canada)



The Sudbury Neutrino Observatory

A collaboration of Chemists, Nuclear Physicists, and Particle Physicists

Canada

Carleton U.
U. British Columbia
U. of Guelph
Laurentian U.
Queens U.

U.K.

U. of Oxford

United States

Brookhaven Lab
LBL
U. of Washington
Los Alamos Lab
U. of Pennsylvania
U. of Texas@Austin

Sudbury Neutrino Observatory

1000 tonnes D_2O

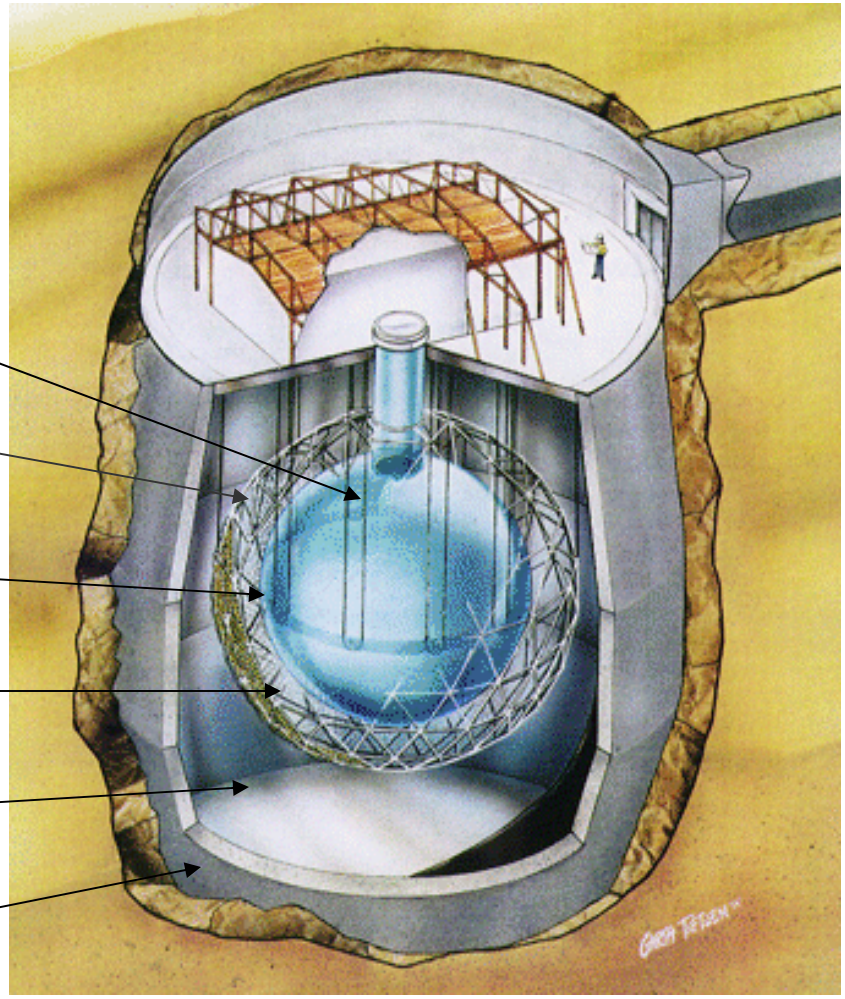
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

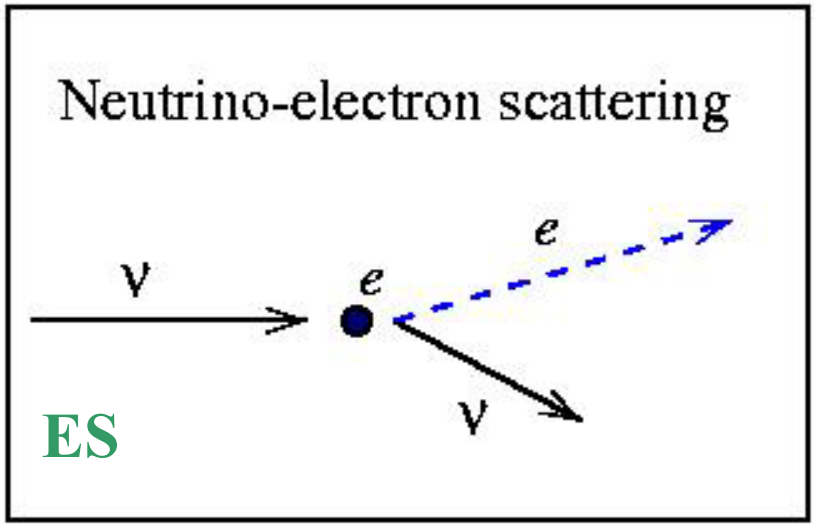
1700 tons Inner Shielding H_2O

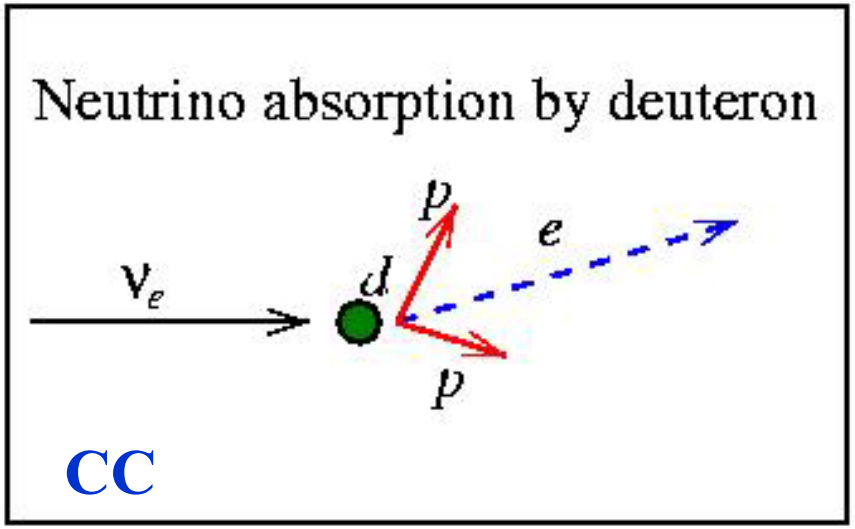
5300 tons Outer Shield H_2O

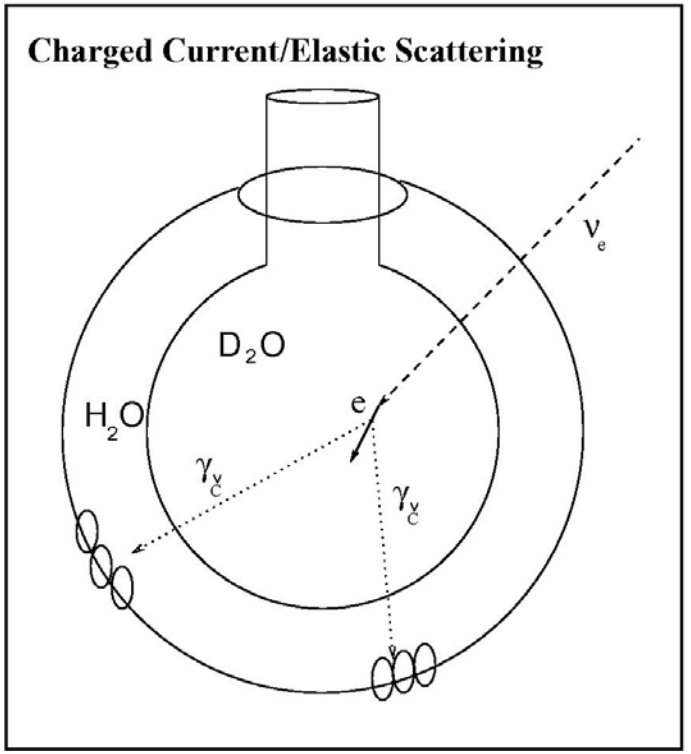
Urylon Liner and Radon Seal



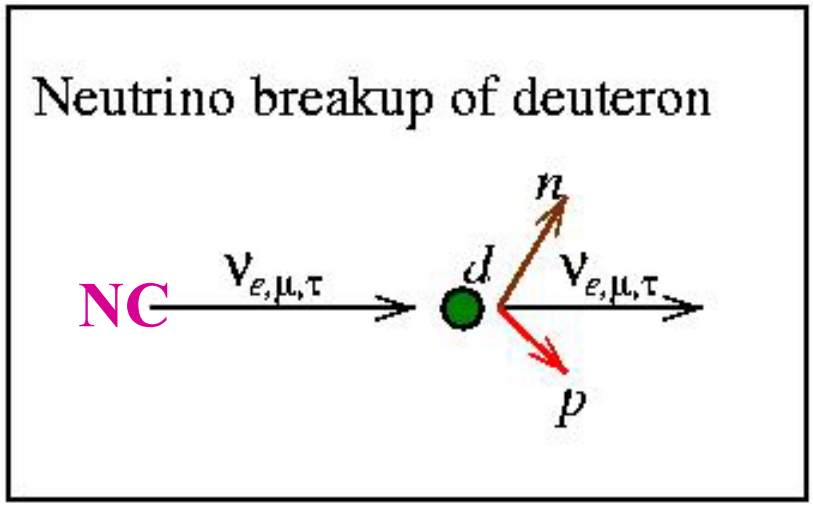
ν Detection in D_2O

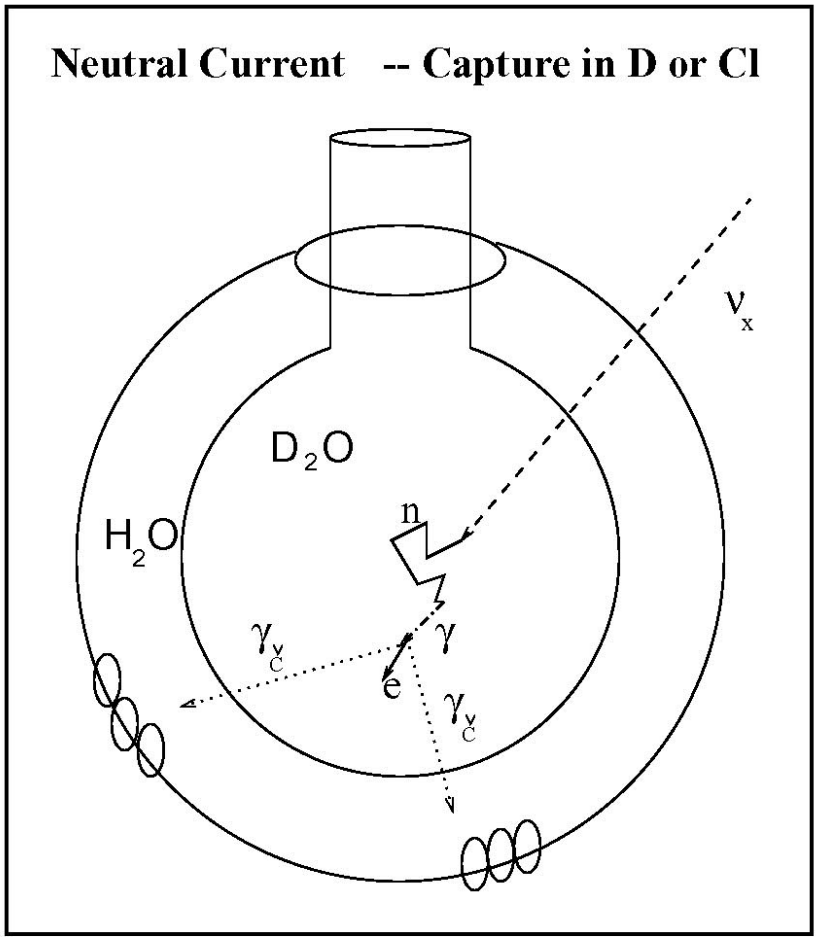






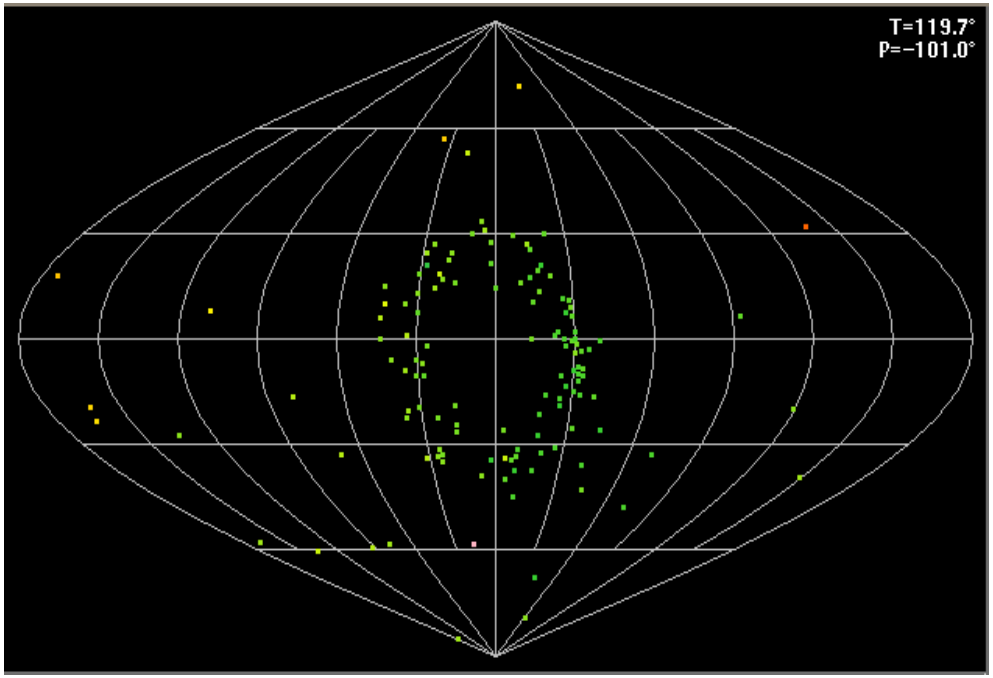
ν Detection in D_2O

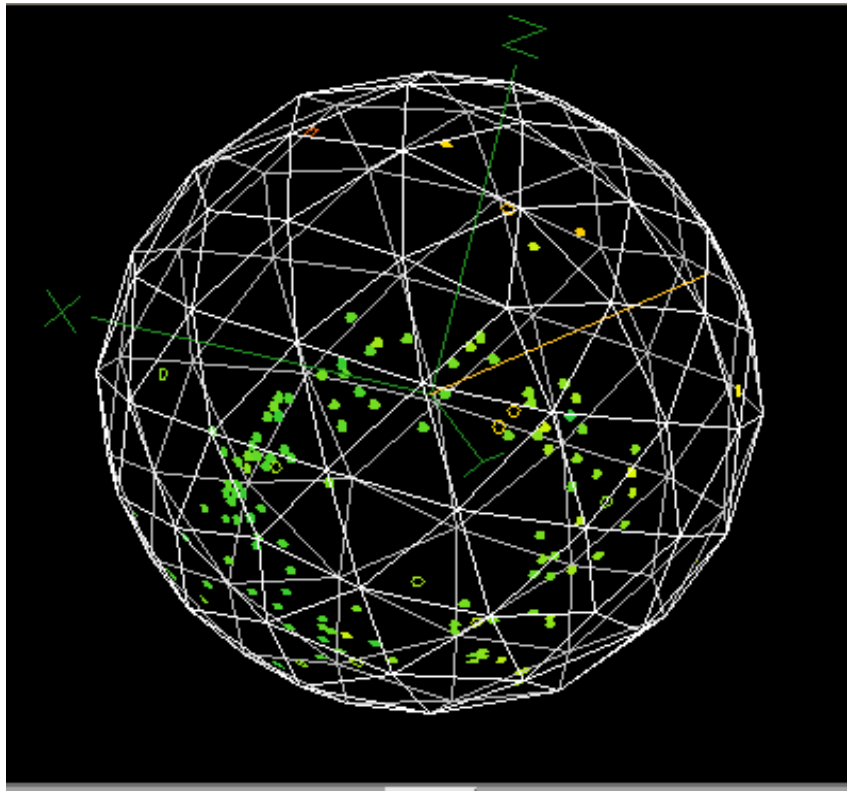




SNO Neutrinos

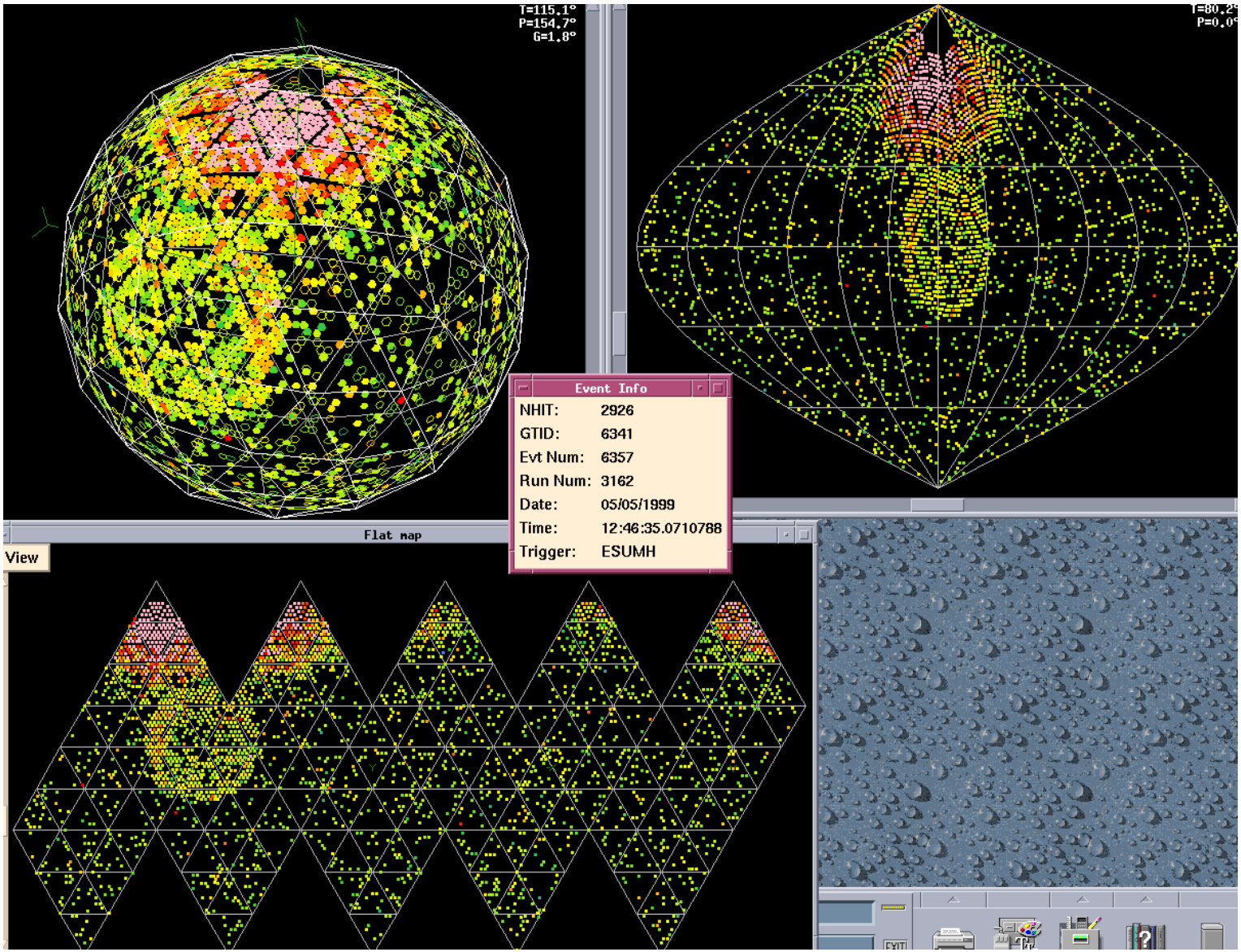
- `Production Running' (Nov 1999-)



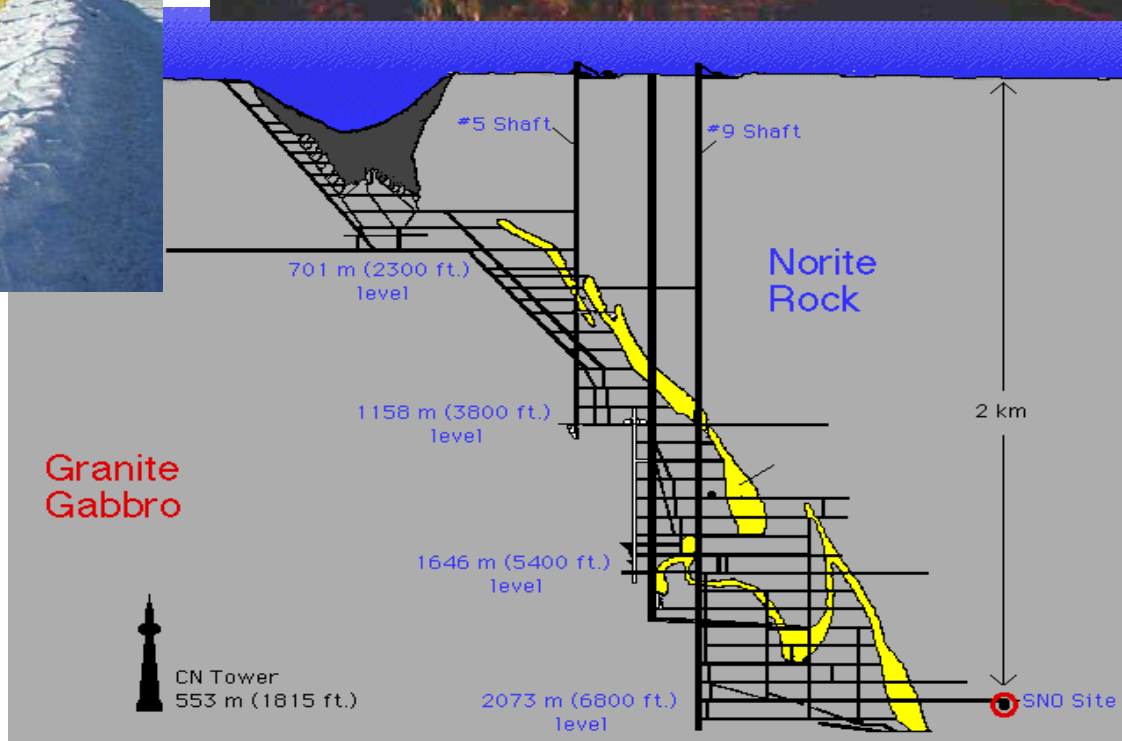


Other Physics

High Energy Atmospheric ν Traveling Through Earth

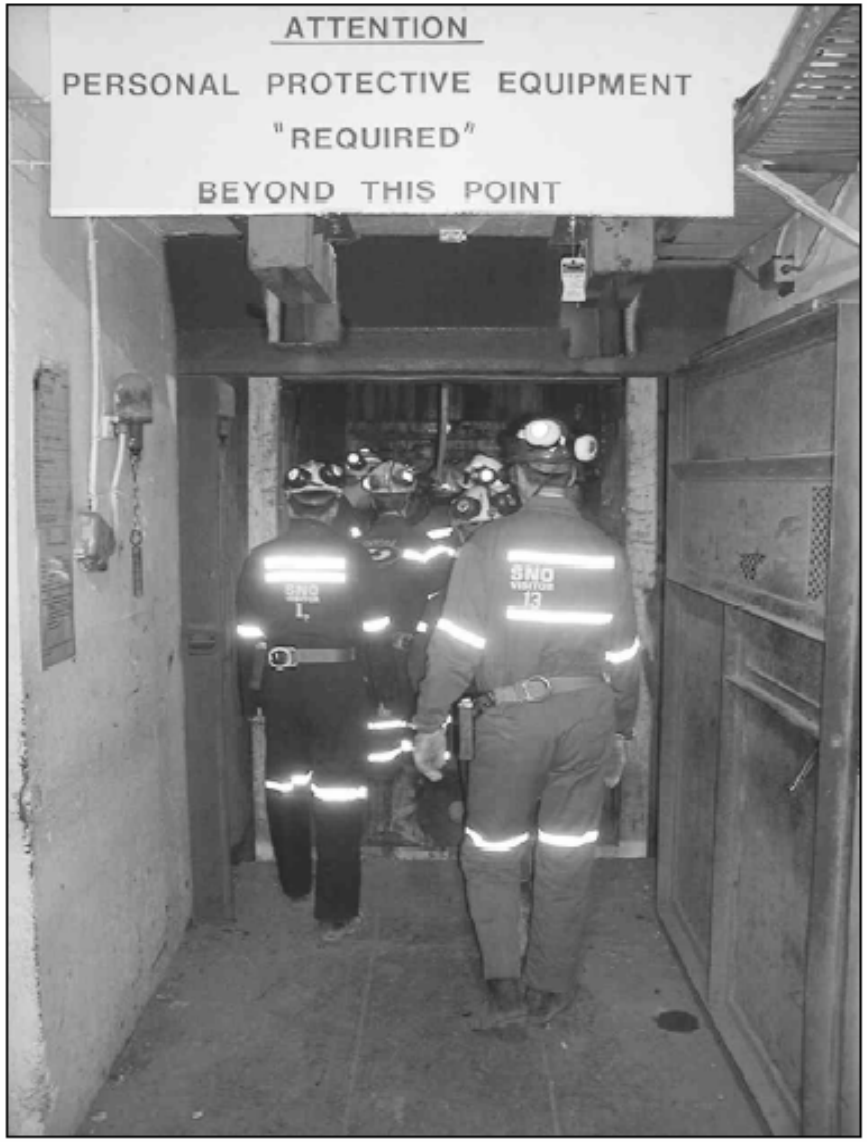


Creighton Mine



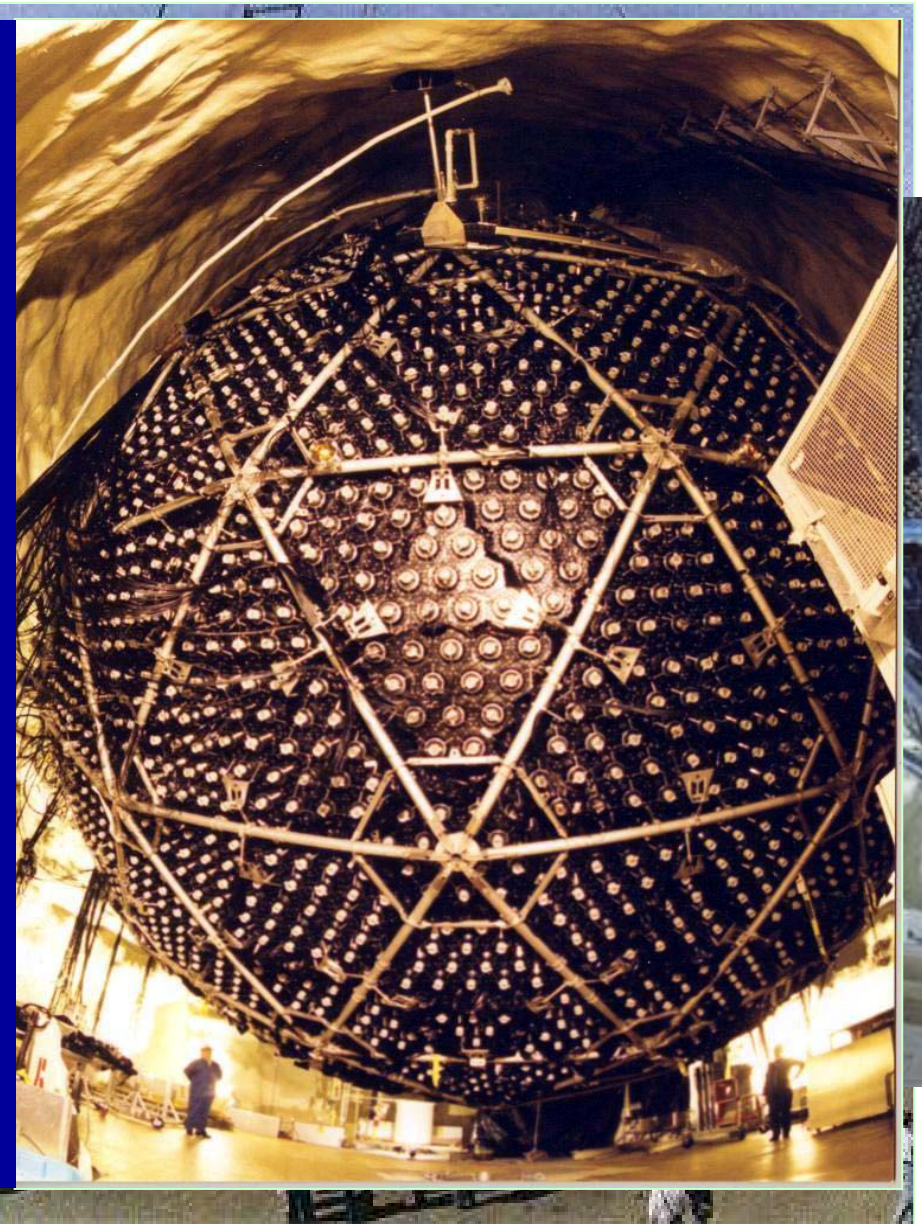
Sudbury Highlights

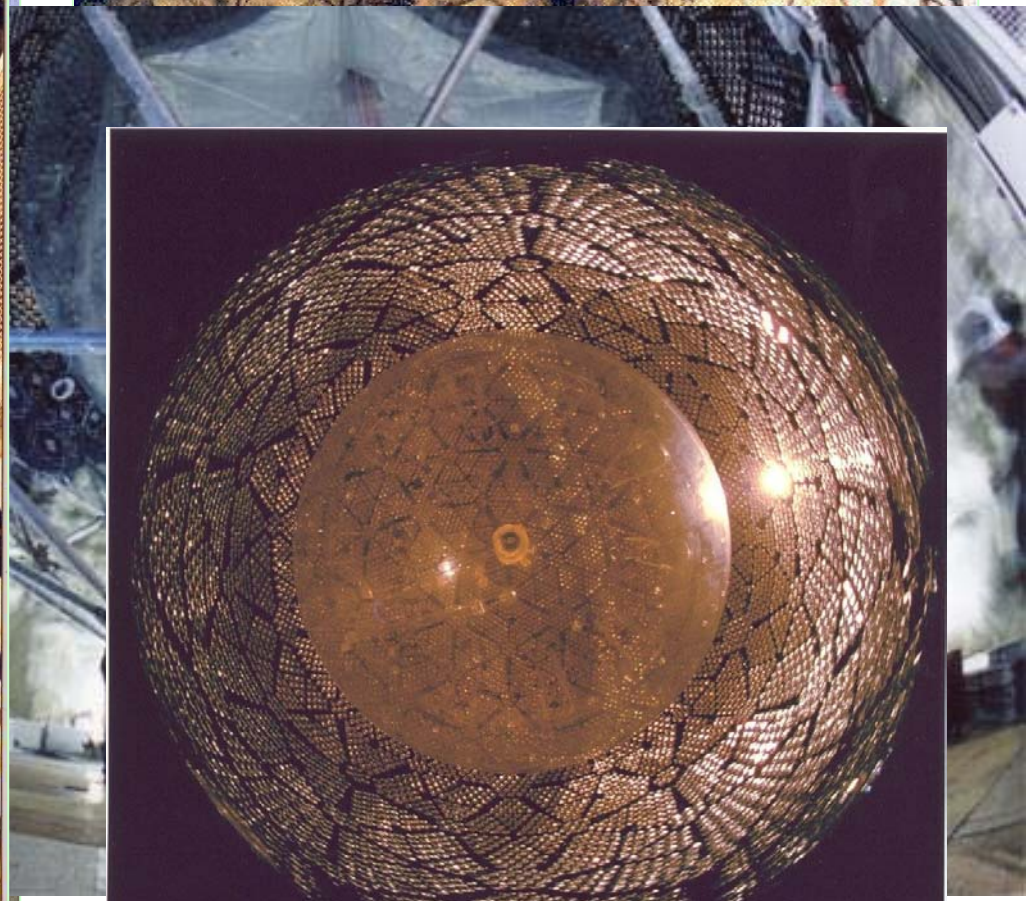
Underground…



…but in the Lab.

Construction

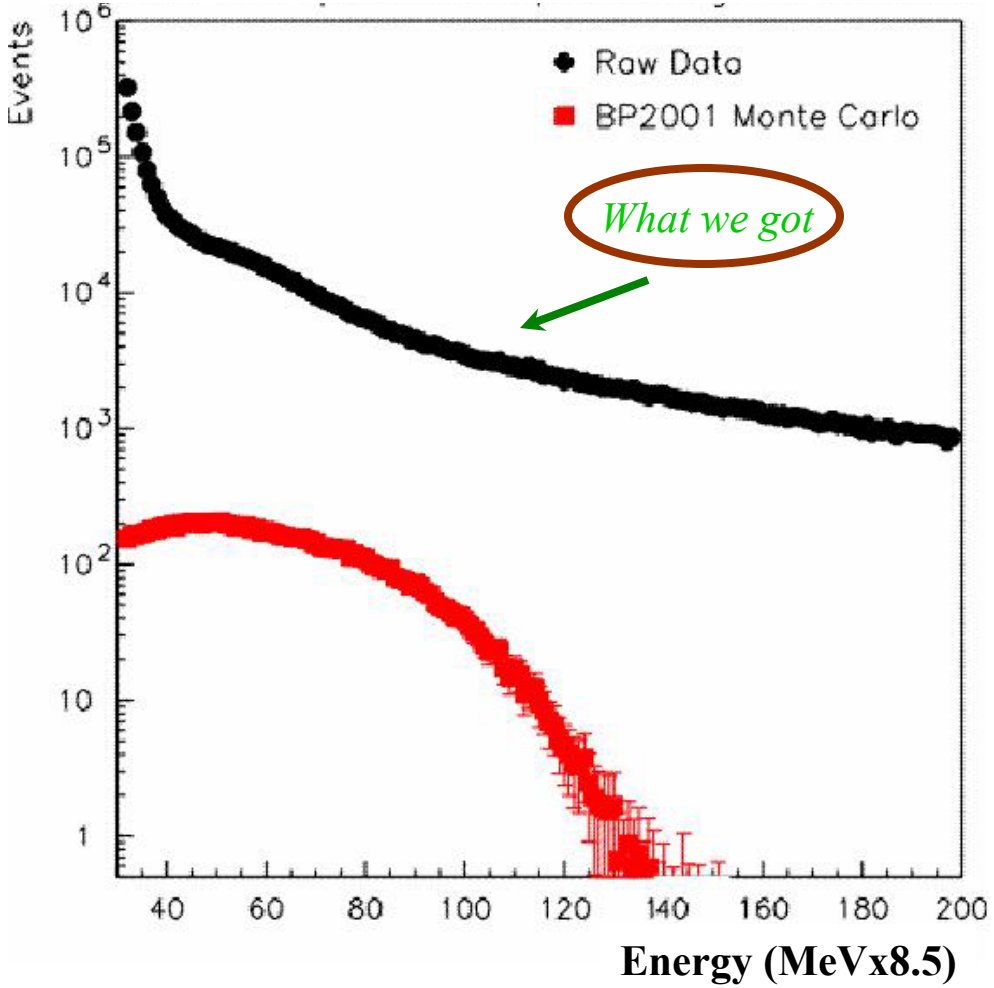




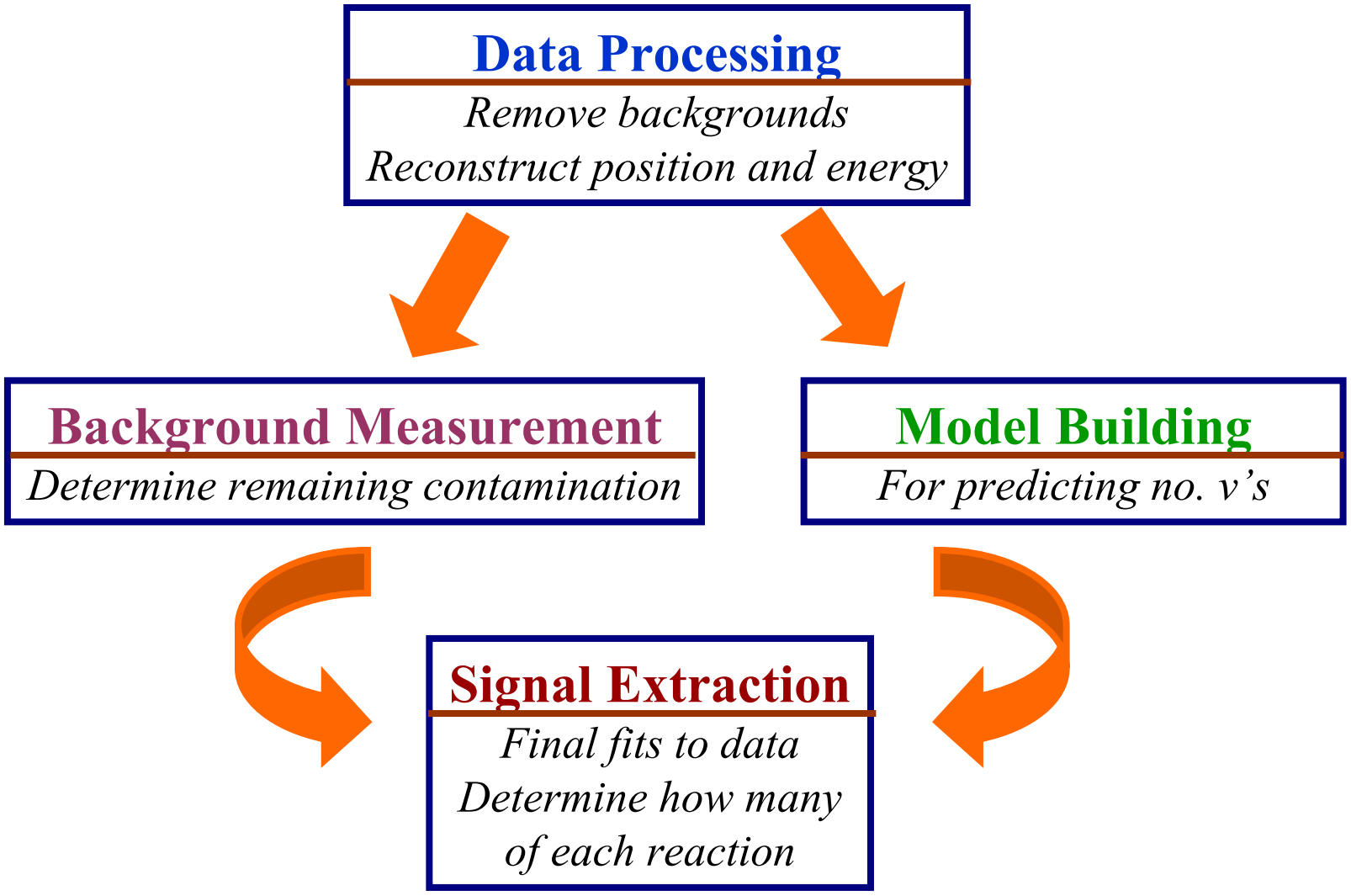
Data Processing

➢ Unexpected Effects!

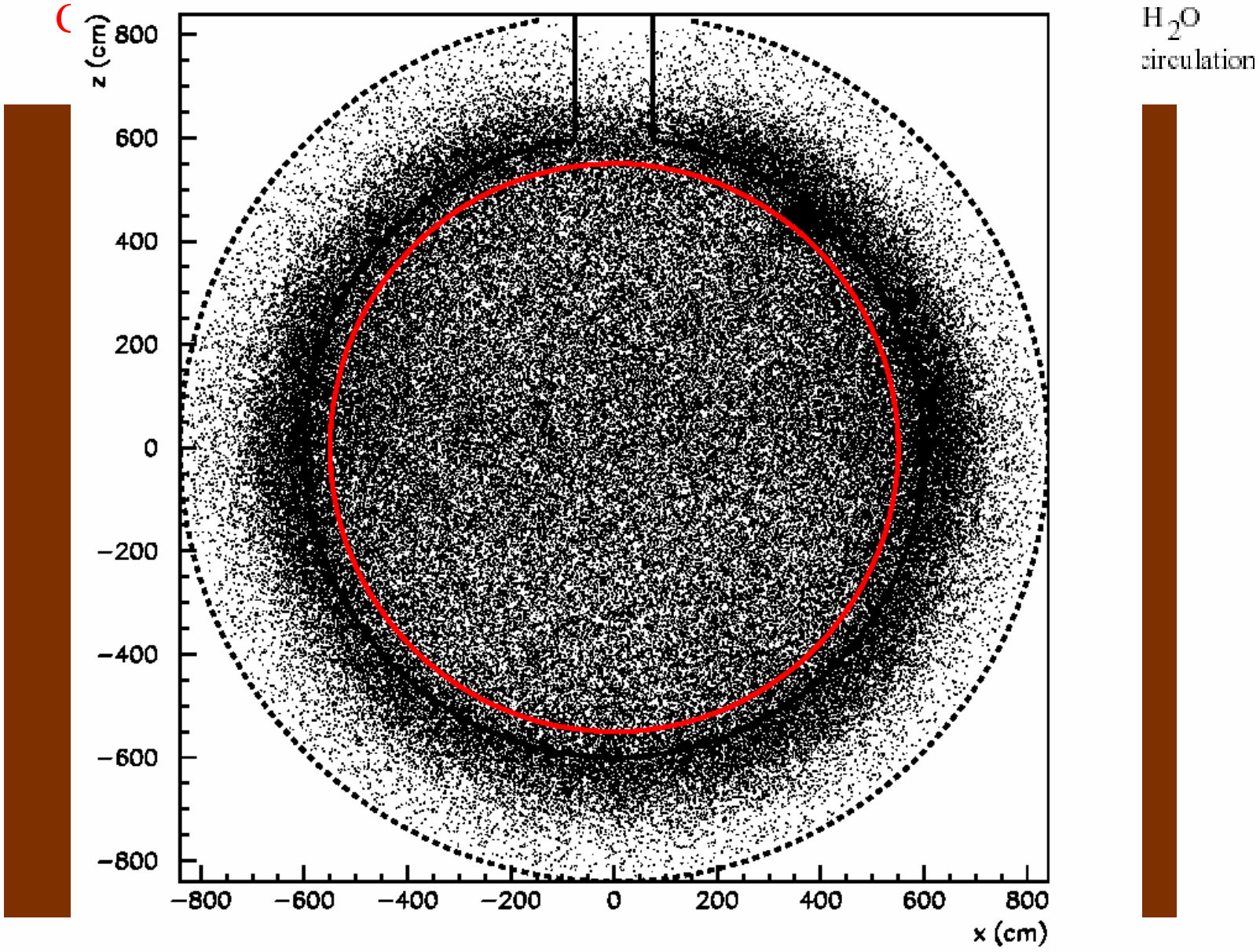
Predicted Raw Energy Spectrum Compared to Data



Extraction Prerequisites

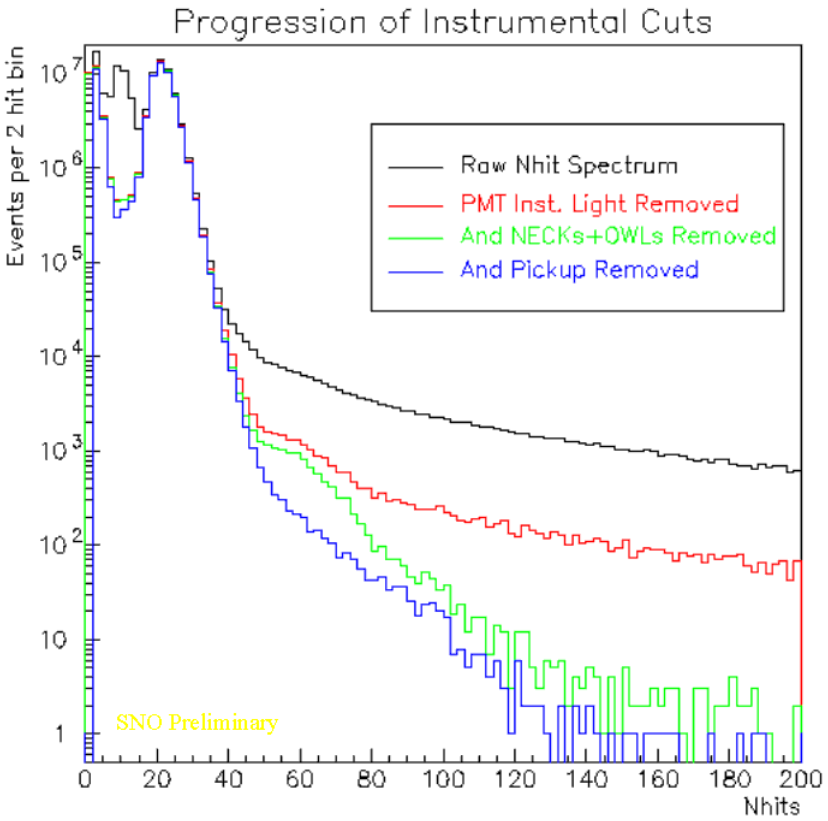


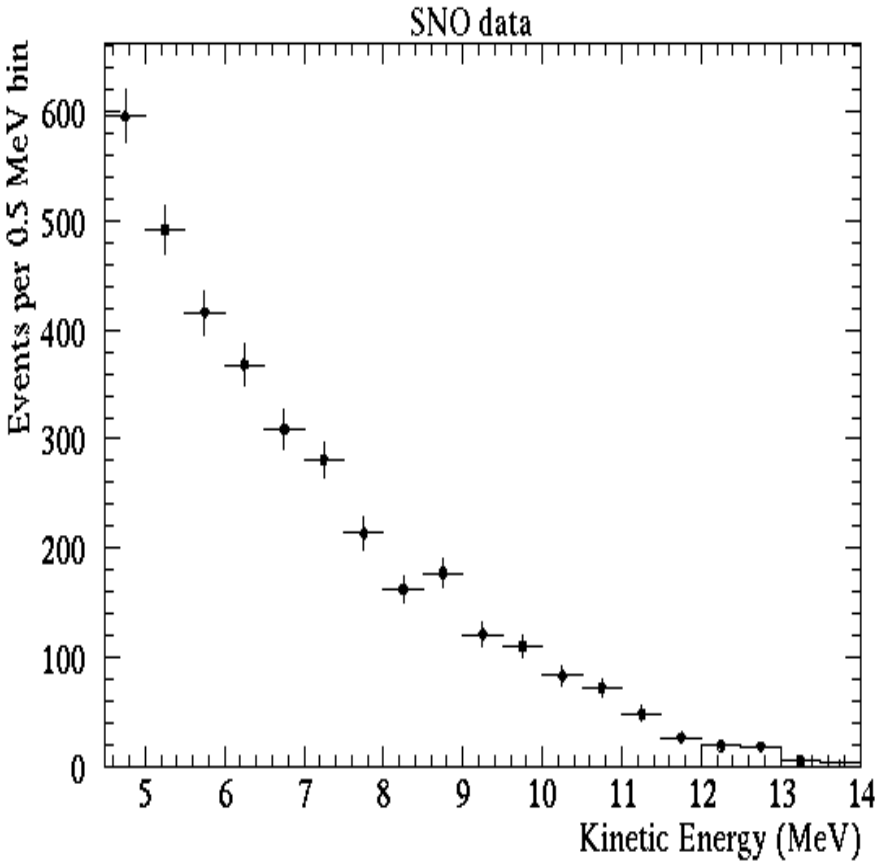
Radioactive Backgrounds



Data Processing

Apply cuts, fit position and direction,
Kinetic energy > 5 MeV, R < 550 cm





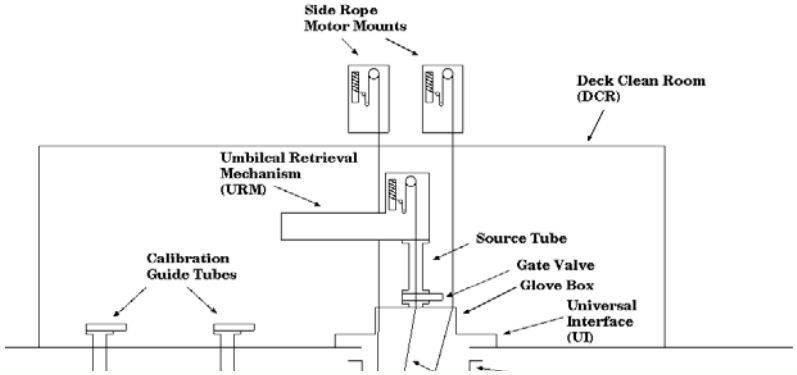
450,188,649 events → 2,928 events

Model Building

➢ How do we know how many we expect?

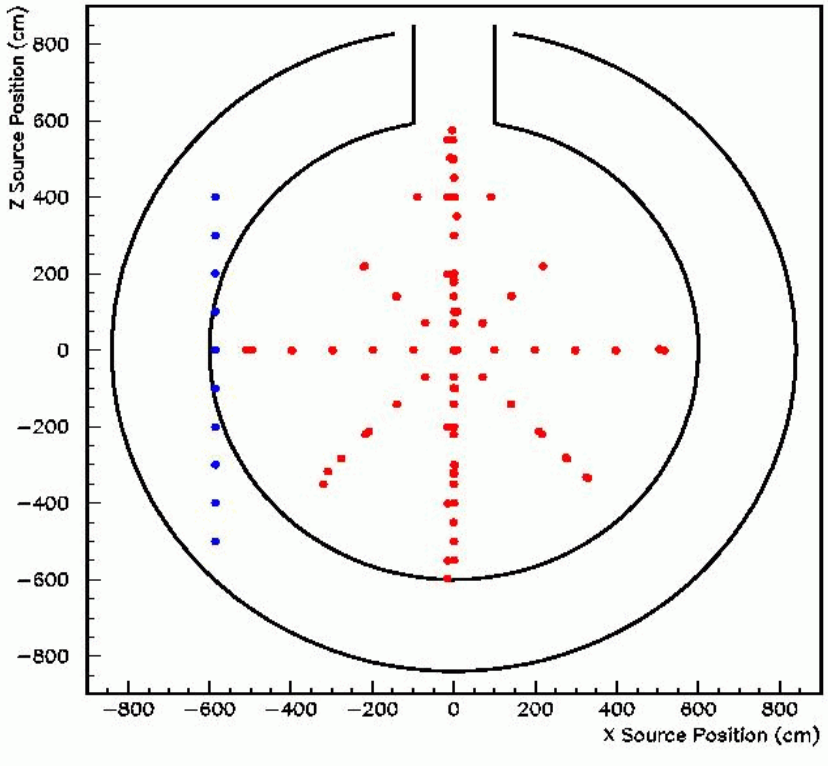
Need to know how detector measures:

- Energy
- Position and direction
- Particle type (e vs. γ)



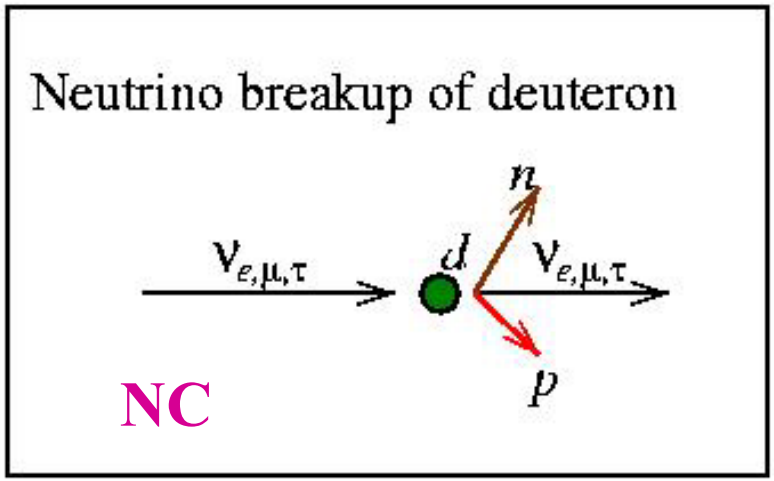
Use radioactive sources:

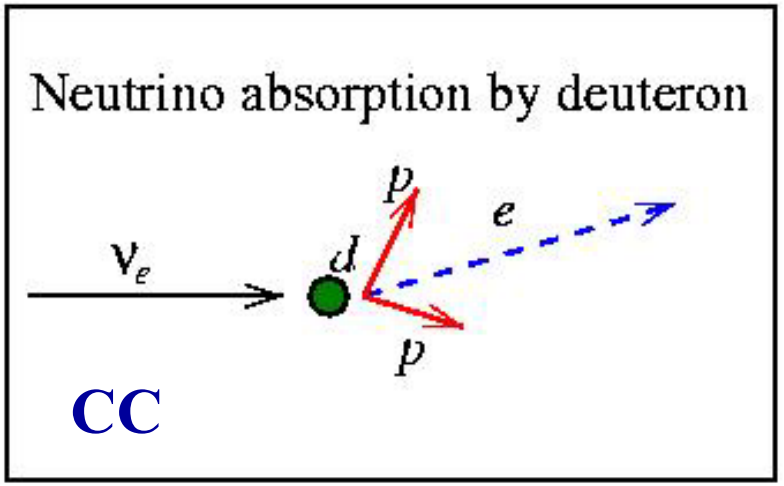
- ^{16}N → 6.13 MeV γ's
- p,T → 19.8 MeV γ's
- Neutrons → 6.25 MeV γ's
- ^{8}Li → β's, E<14 MeV
- Encapsulated U and Th sources



Results

Herb Chen's original idea becomes possible:





(sensitive to all flavors equally)

(sensitive only to ν_e)

Main Question: Is number of ν's measured with NC > CC??

Signal Extraction

➢ Flux Measurements

SNO measurements: (units 10^6 cm^{-2} s^{-1})

$$\phi_{\rm CC}^{\rm SNO} = 1.76^{+0.06}_{-0.05}({\rm stat.})^{+0.09}_{-0.09}\ ({\rm syst.})$$

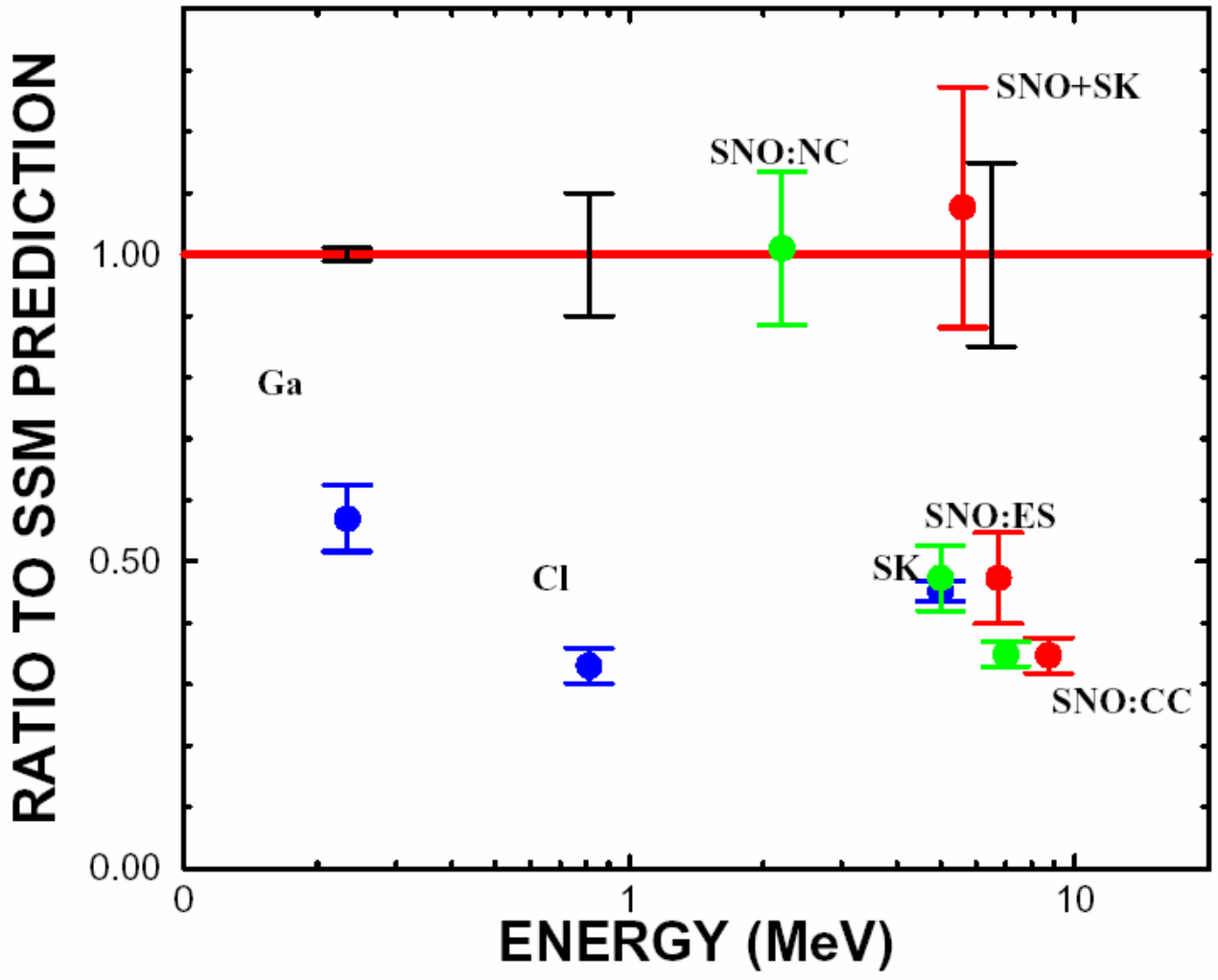
$$\phi_{\rm ES}^{\rm SNO} = 2.39^{+0.24}_{-0.23}({\rm stat.})^{+0.12}_{-0.12}\ ({\rm syst.})$$

$$\phi_{\rm NC}^{\rm SNO} = 5.09^{+0.44}_{-0.43}({\rm stat.})^{+0.46}_{-0.43}\ ({\rm syst.})$$

Total number of neutrinos much bigger than ν_e's!

Phase I (Pure D_2O) Results

➢ SNO Compared to Other Solar Expts.



Looking for the Matter Effect

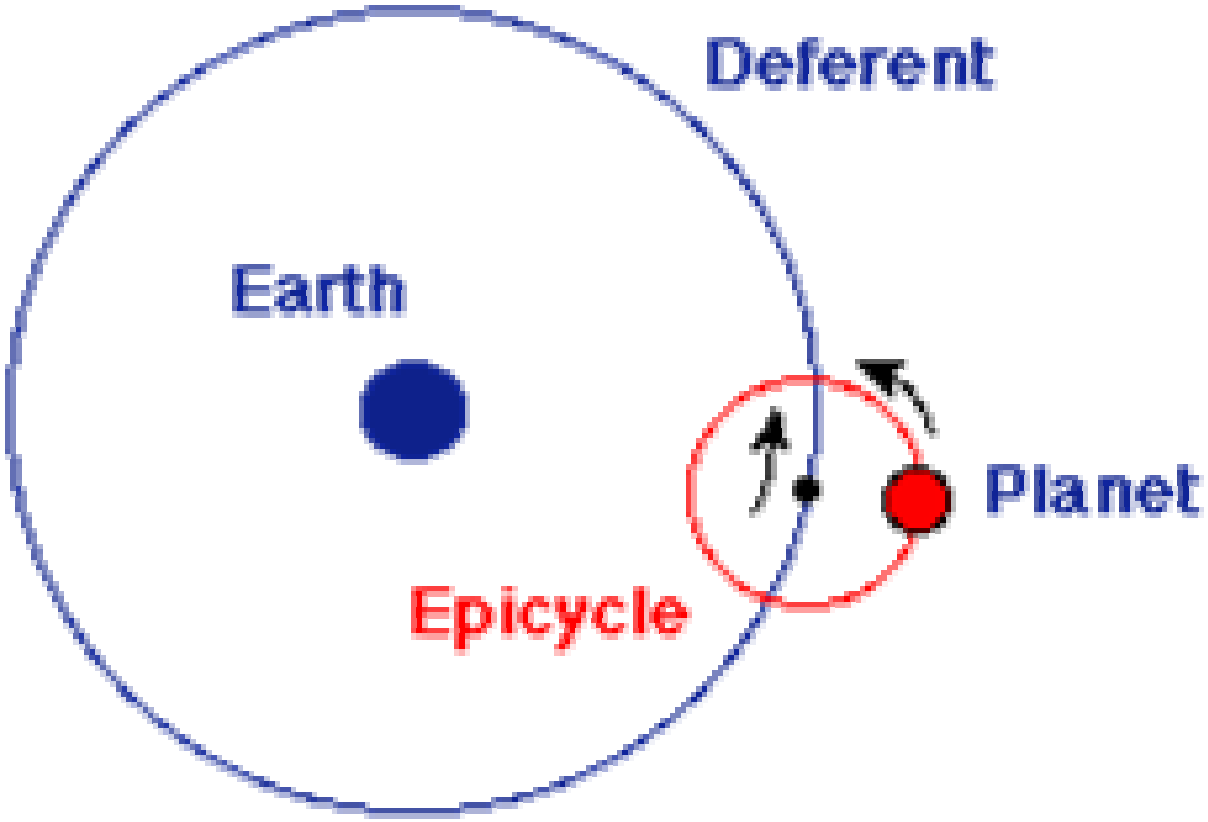
Do ν_e's `regenerate' during the night?

$$A_E = 7.0\% \pm 4.9\%^{+1.3}_{-1.2}\%$$

Hard to say…so far.

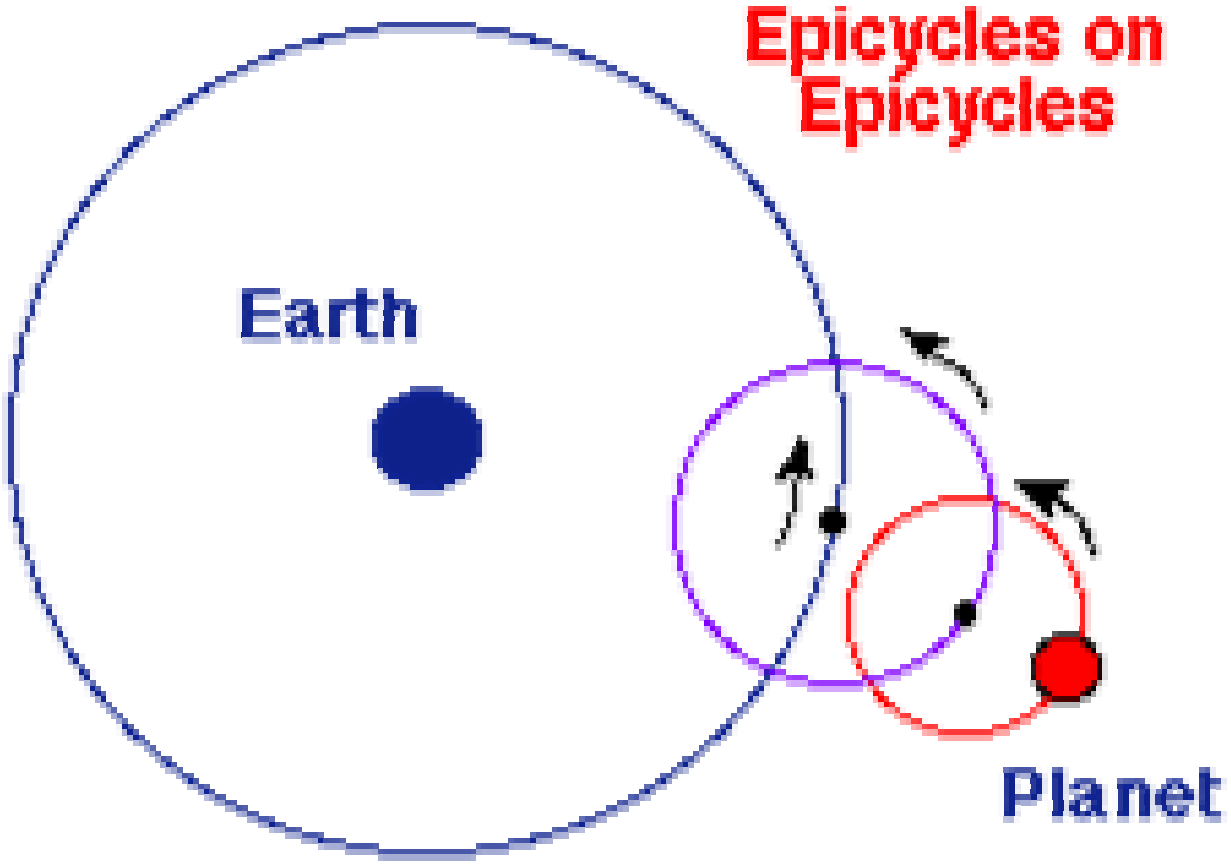
So? Is the Standard Model Dead?

The Standard Model of Particle Physics



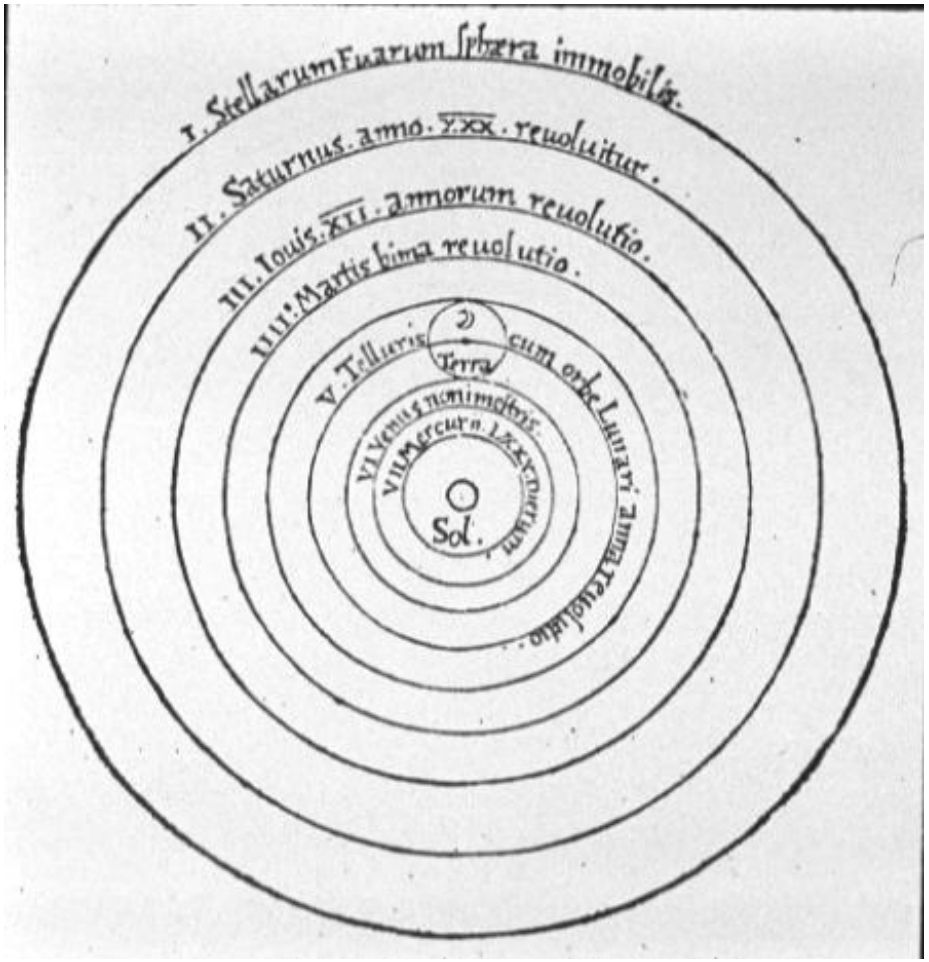
So? Is the Standard Model Dead?

The Standard Model + neutrino flavor transformation



So? Is the Standard Model Dead?

The Next Theory?



Uncharted Waters

Physics Implications

➢ Solar Core Temperature

Standard Solar Model Predicts

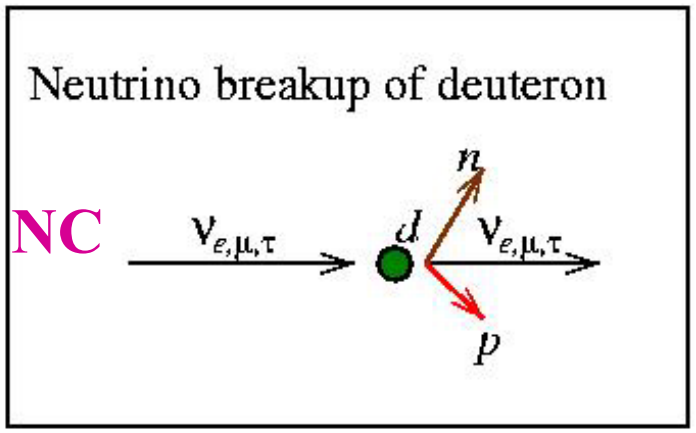
$$\phi_{\upsilon}^{\ ^8B} \propto T^{25}$$

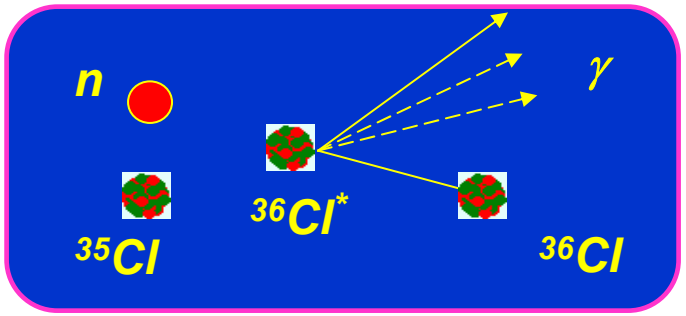
$$\rightarrow T_{\text{Sun}}^{\text{core}} \cong 15.6 \times 10^6\,\text{K}$$

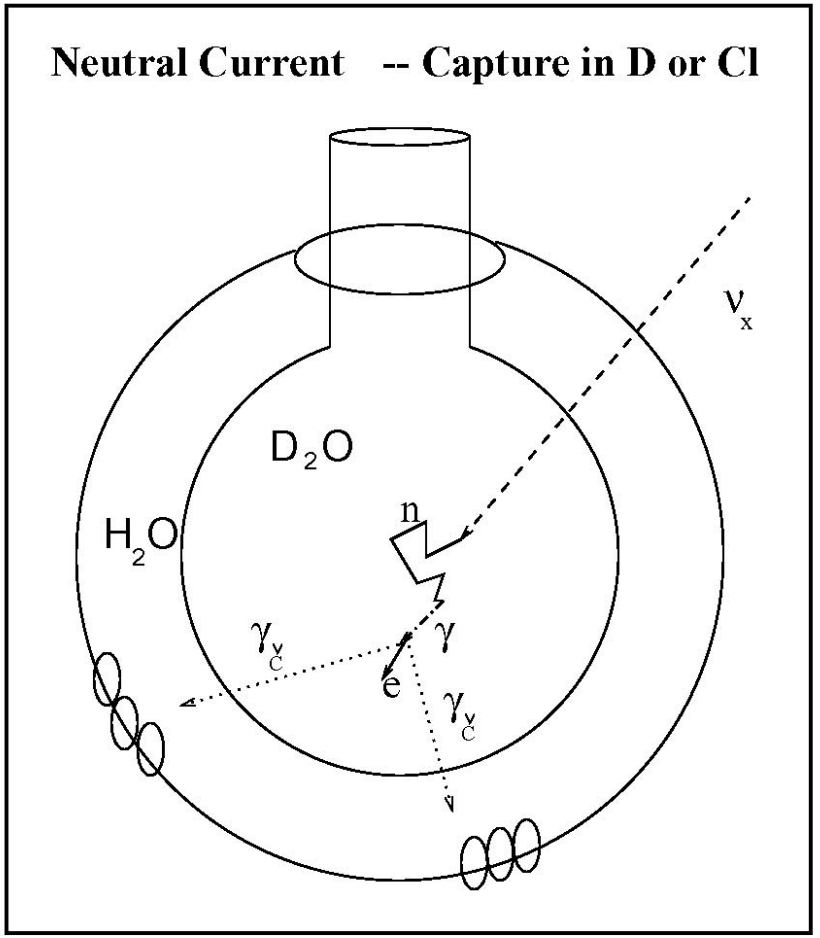
(the start of solar neutrino astronomy…)

ν Detection in Salty D_2O (Phase II)

2 tons of NaCl added June 1, 2001







^{35}Cl has ~4x higher n capture rate than D
Total E emitted ~ 2 MeV higher

Measure total solar ν flux with precision near 5%

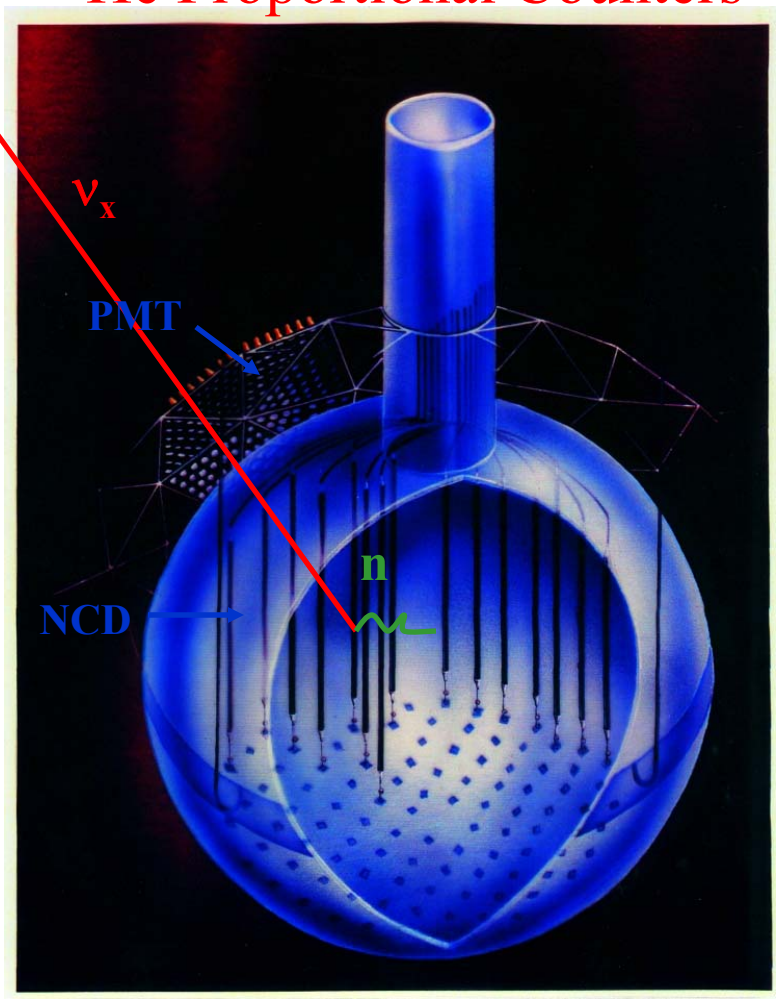
SNO Phase III (NCD Phase)

➢ Detecting Neutrons Directly

Beginning ~September 2003

‘Absorption’ of neutrons also makes it easier to measure ν energy spectrum

^{3}He Proportional Counters



Summary

- SNO sees first direct evidence of ν flavor change
- Thirty year old Solar Neutrino Problem solved!
- Neutrinos can now help us understand Sun
- Discovery era for ν physics just beginning